BLACK HOLES IN THE EARLY UNIVERSE

Dan Hooper – Fermilab/University of Chicago

Gran Sasso Science Institute, Astroparticle Colloquium

February 10, 2021

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),*

Constraints on Primordial Black Holes from Big Bang Nucleosynthesis Revisited *(arXiv:2006.03608),*

With Nikita Blinov, Celeste Keith, Gordan Krnjaic, Sam McDermott, John March-Russell and Rudin Petrossian-Byrne

See also: Barrow *et al.* (1991), Baumann *et al.* (2007), Morrison *et al.* (2019)

Early History of Black Holes

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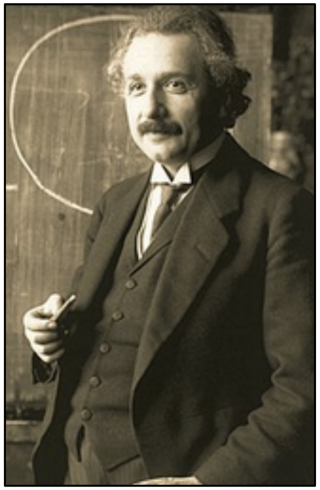
1915 – Einstein published the field equations of general relativity

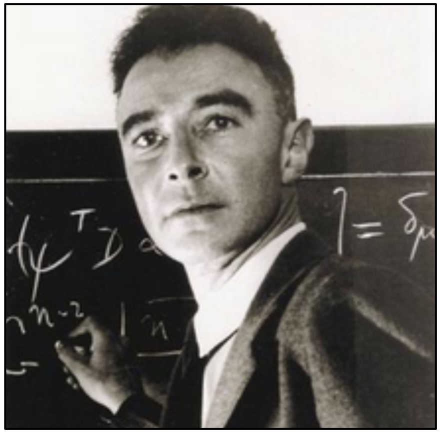
1915 – Karl Schwarzschild identified the first exact solution to the GR field equations, for the case of a non-rotating, spherically symmetric mass



Early History of Black Holes

1931 – Subrahmanyan Chandrasekhar showed that for a non-rotating body of electron-degenerate matter with a mass greater than 1.4 $M_\odot$, there are no stable solutions; nothing to prevent further collapse (it was later recognized that such objects would become neutron stars)

1939 – Robert Oppenheimer and collaborators predicted that neutron stars more massive than a particular value (the Tolman-Oppenheimer-Volkoff limit, now estimated to be ~2.2 $M_\odot$) would collapse further; no known physics would prevent from becoming infinitely small and dense



The Golden Age of Black Holes

1958 – David Finkelstein identified the Schwarzschild surface as an "event horizon", separating causally disconnected regions

1963 – Roy Kerr found the exact solution to the GR field equations for a rotating black hole

1965 – Ezra Newman found the exact solution to the GR field equations for an electrically charged black hole

Late 1960s – Roger Penrose and Stephen Hawking demonstrated that singularities are a generic feature of GR

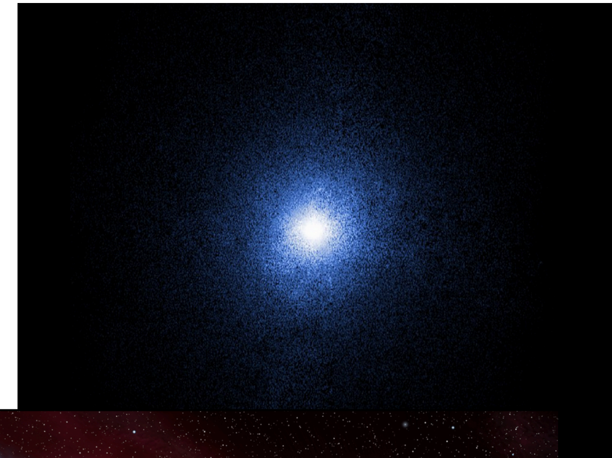
1974 – Hawking showed that quantum field theory implies that black holes should radiate like a black body, with a temperature that is inversely proportional to their mass


Penrose


Hawking

Evidence For Black Holes

- The first discovery of a black hole was the bright X-ray source, Cyg X-1 (1970s) – a ~10-20 stellar-mass black hole that is actively accreting matter from a companion
- Dozens of black holes in binary systems have since been observed



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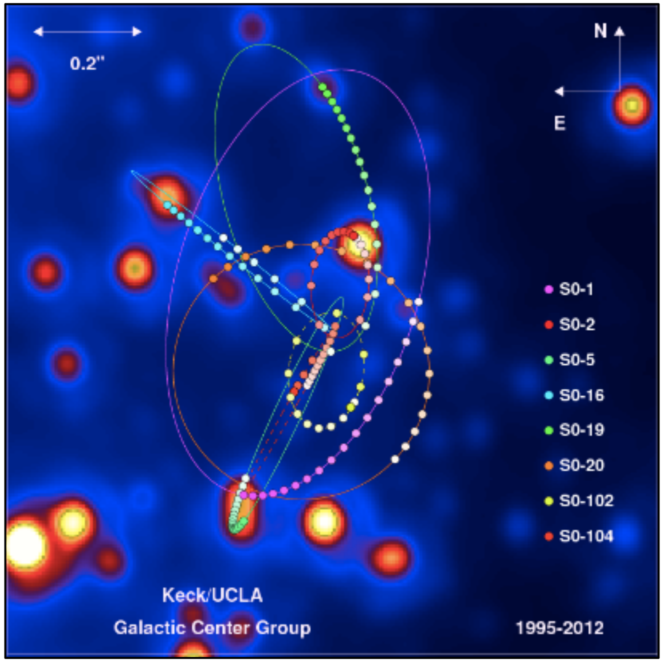
- Perhaps the clearest example of this is the Milky Way's own Sgr A*



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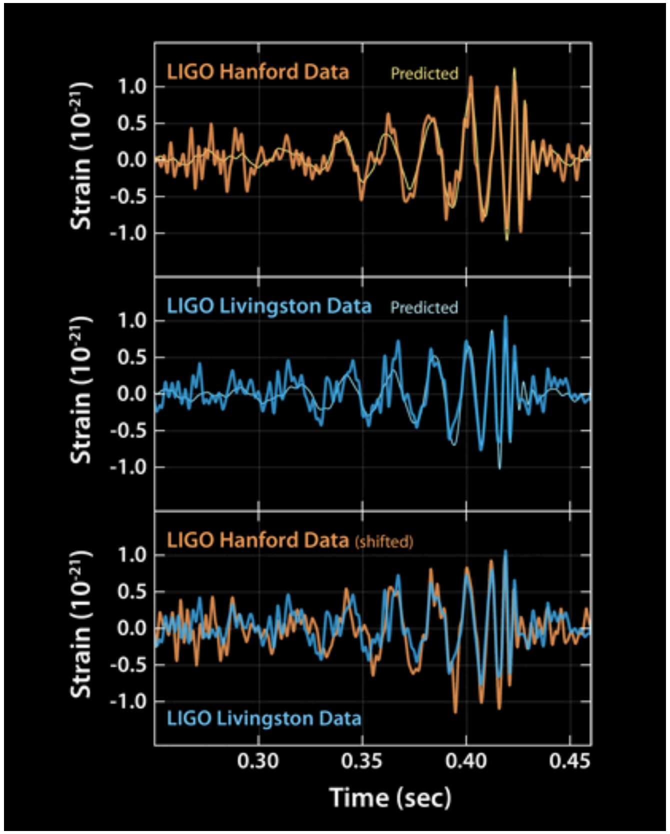

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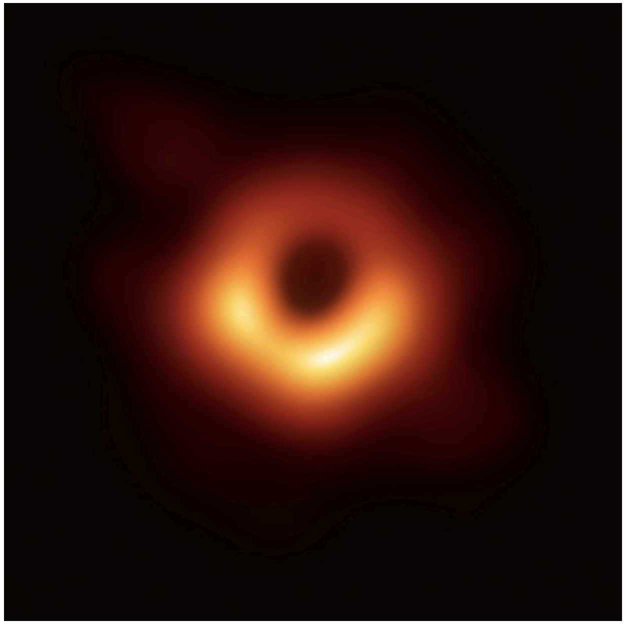

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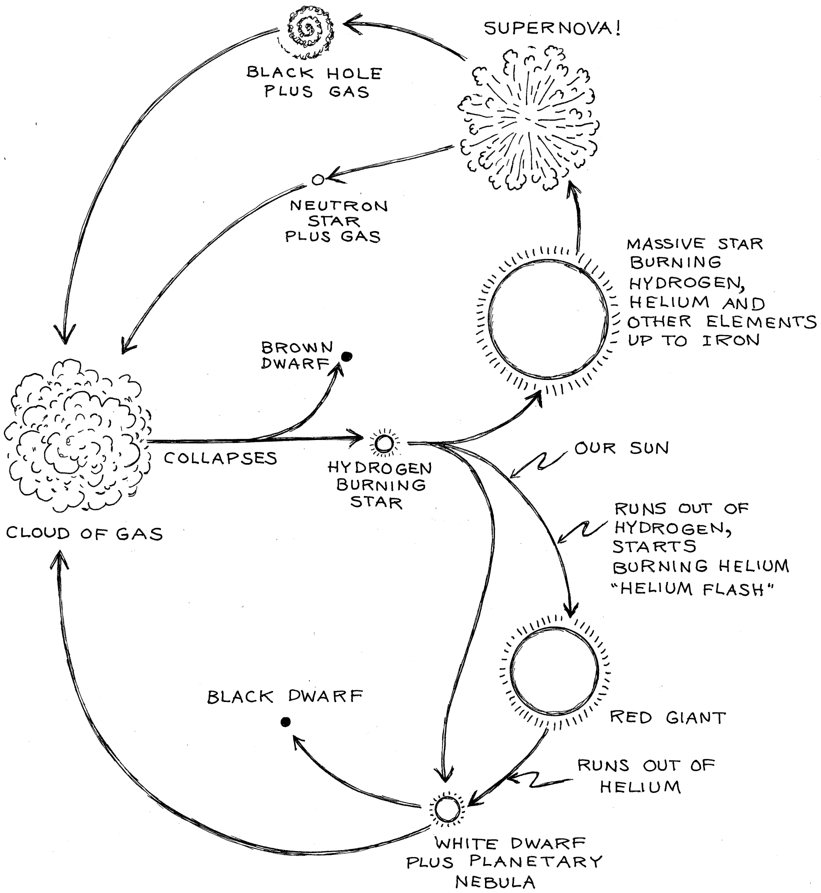
- In 2019, a supermassive black hole (at the center of the galaxy M87) was imaged for the first time by the Event Horizon Telescope

Where Do Black Holes Come From?

Stellar Mass Black Holes

- The most massive stars ultimately collapse to form black holes with masses in the range of a few to a few tens of $M_{\odot}$
- In the first generations of star formation, very massive stars may have led to the production of even larger black holes



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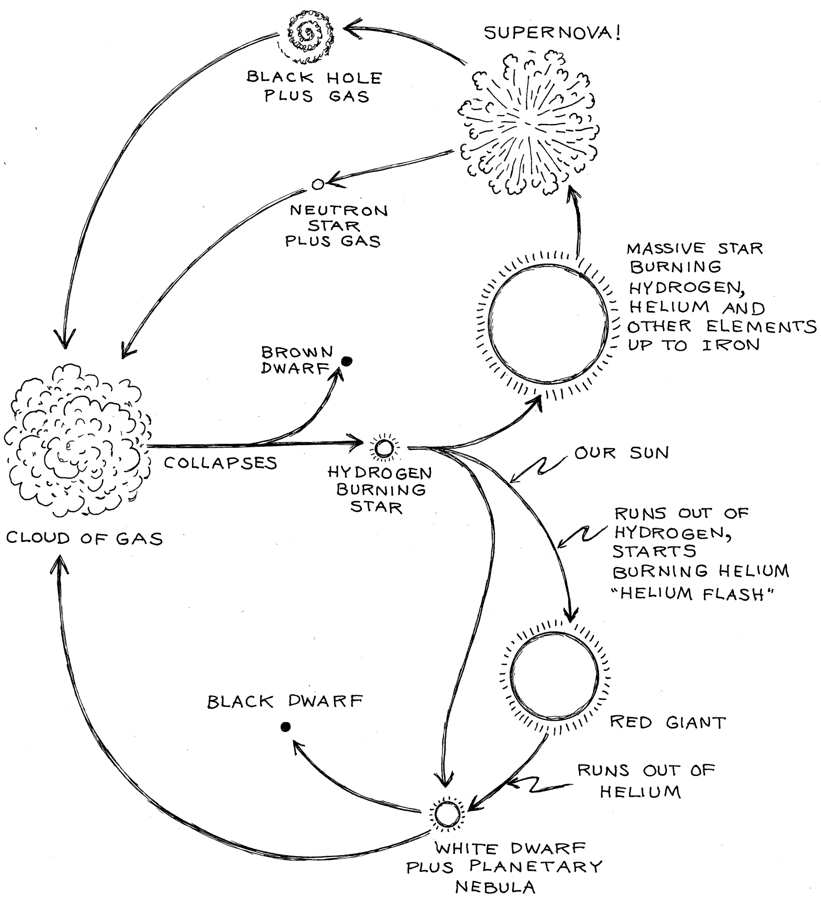
Supermassive Black Holes

- Black holes can grow through accretion and through mergers, ultimately reaching millions or even billions of solar masses
- The seeds of supermassive black holes remains a topic of debate



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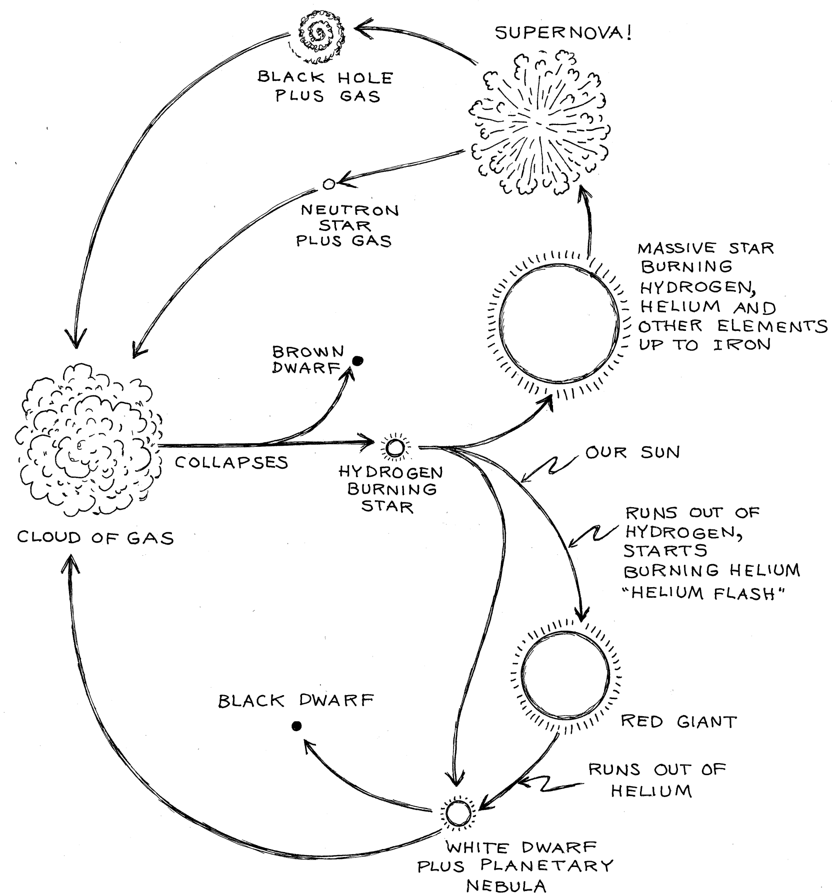
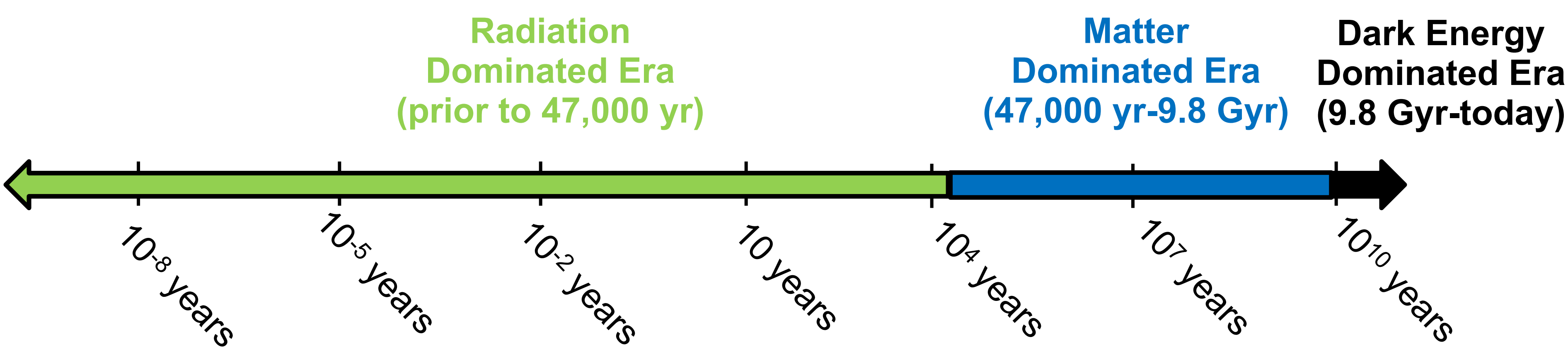
Primordial Black Holes?

- It is possible that black holes may have formed in the early universe, with no direct relationship to stars



What We Know (and don't) About the Early Universe

- Cosmology textbooks typically break the history of our universe into three eras: radiation domination, matter domination, and dark energy domination



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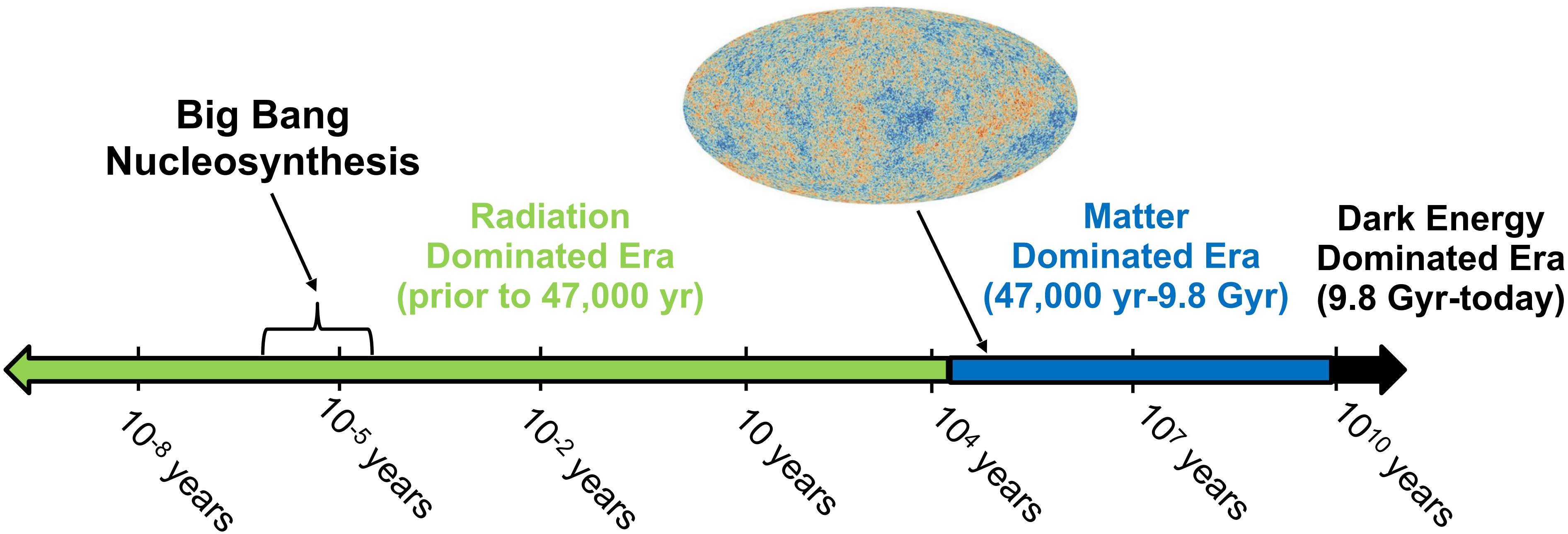

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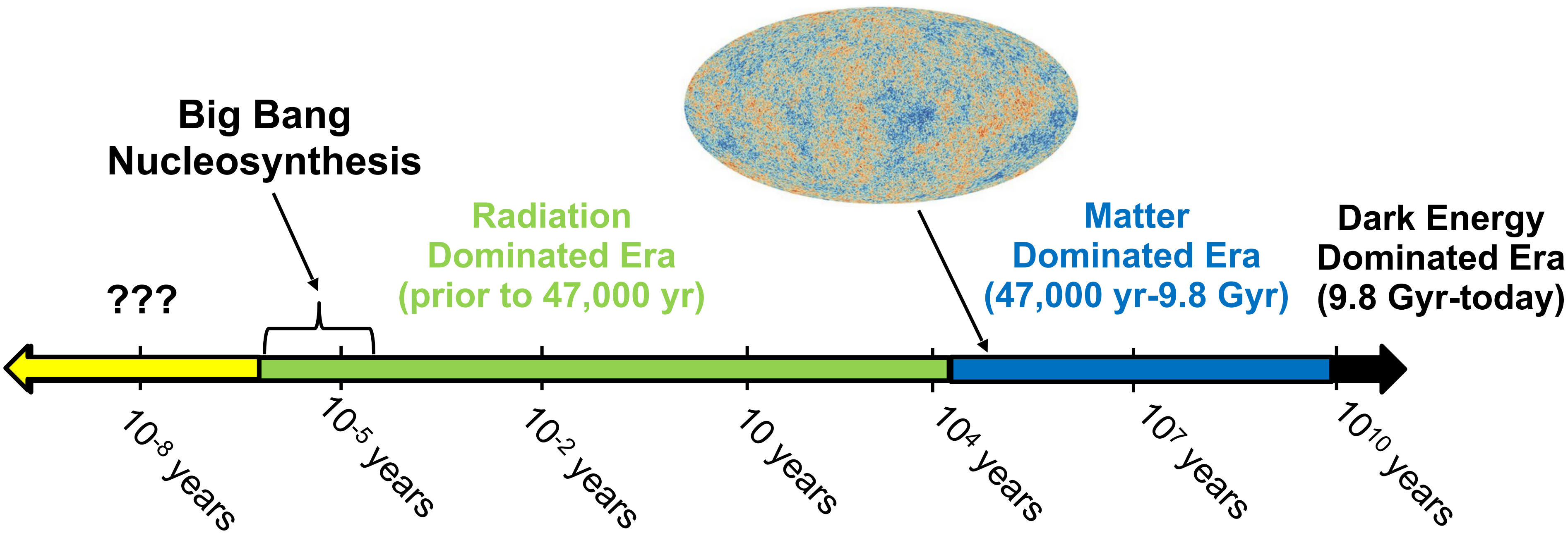
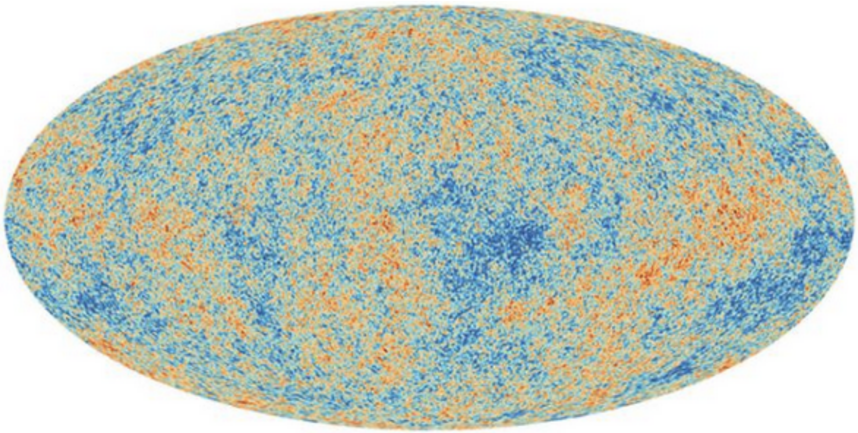
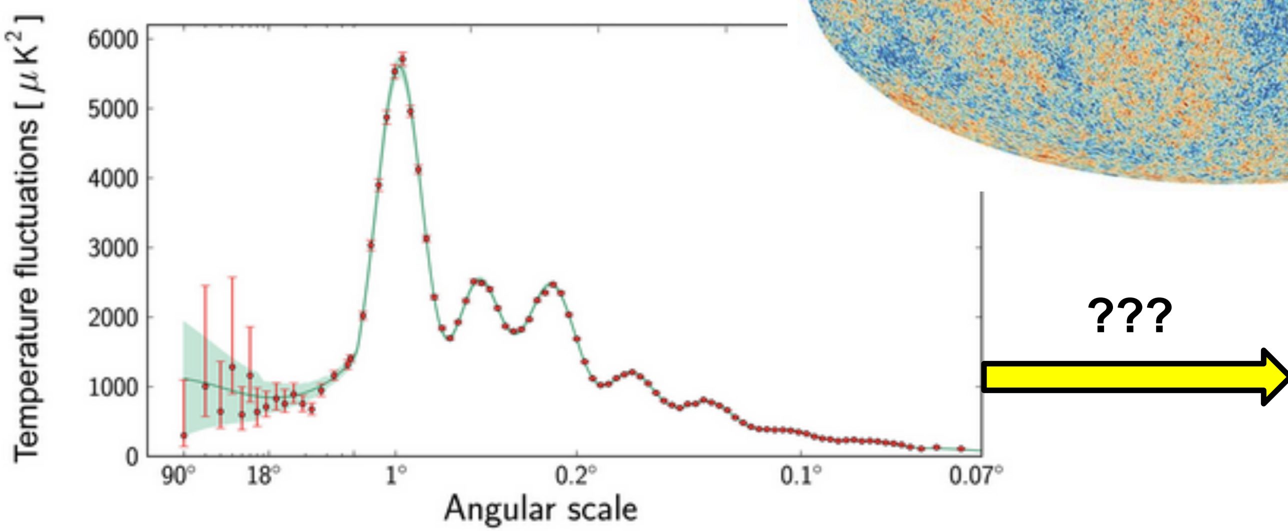


- Prior to BBN (~1-10 s), we simply don't know whether radiation or something else dominated the energy density of our universe

What We Know (and don't) About the Early Universe

- We also know that the density of the early universe was very uniform ($\delta\rho/\rho \sim 10^{-5}$), at least on the scales that we can observe in the cosmic microwave background and in large scale structure
- On smaller scales, however, we can only extrapolate (*ie.* guess) – large inhomogeneities are possible on small scales





Black Holes in the Early Universe

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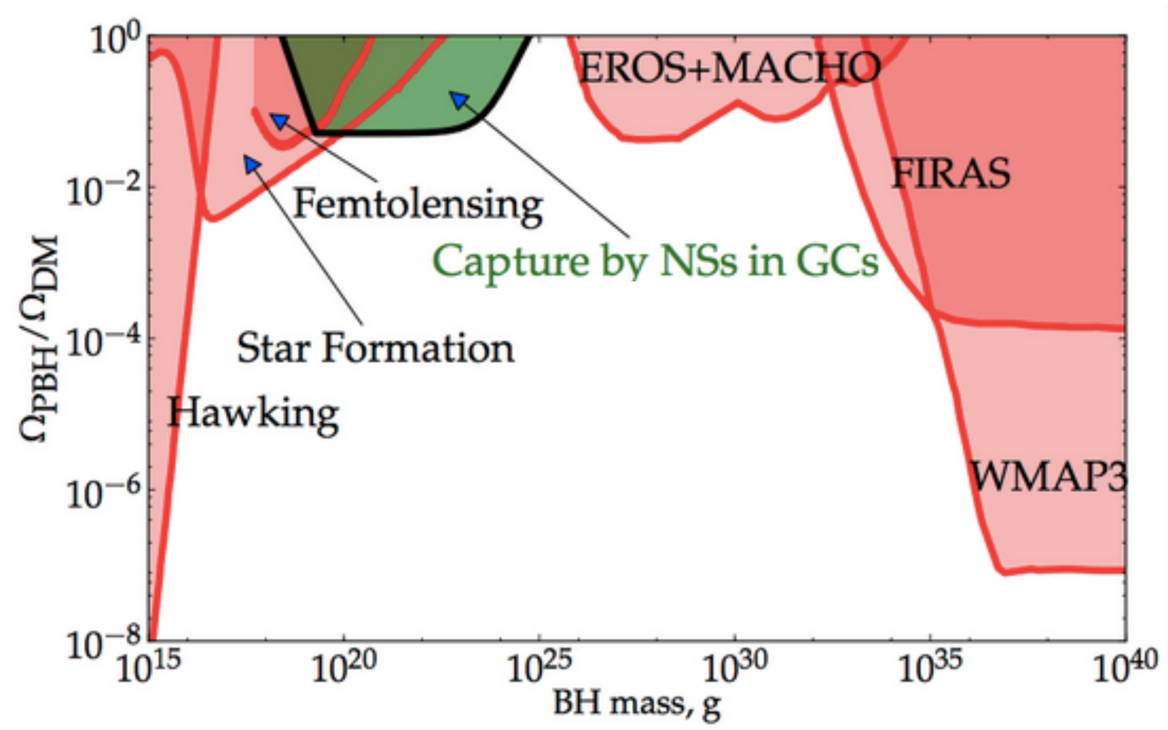
- If there were large inhomogeneities on small scales in the early universe, this could have led to the efficient formation of primordial black holes
- Across a wide range of masses, there are stringent constraints on the abundance of black holes in our universe; in particular, black holes probably don't make up most of the dark matter
- But what about much smaller (*ie.* lower mass) black holes?



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:

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

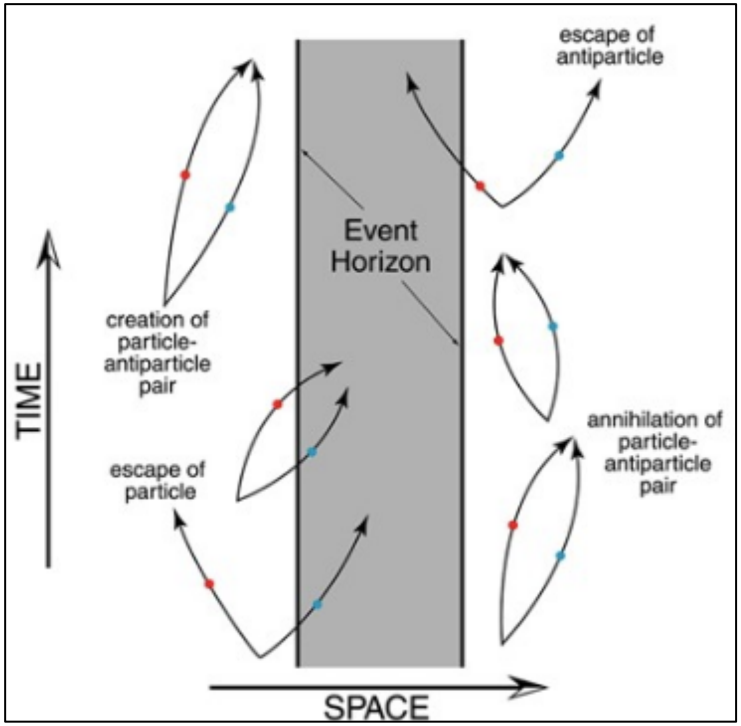
- For reheating temperatures in the range of T_{RH}~10^{10}-10^{15} GeV, this corresponds to horizon masses of M_{hor}~10^{2}-10^{12} grams
- From this perspective, it seems particularly well motivated for us to consider primordial black holes that were formed with masses in roughly this range (more massive black holes could only form 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; a highly model dependent question

Hawking Evaporation

- In 1974, Stephen Hawking made a series of theoretical arguments that black holes should evaporate, radiating particles from their event horizons with an approximately thermal distribution
- Cartoon picture: when a pair of virtual particles is created near the event horizon of a black hole, these particles can be causally disconnected, making them unable to annihilate
- It follows from these arguments that the event horizon of a black hole should emit particles as a blackbody, with the following temperature:

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

- All particle species lighter than $T_{\rm BH}$ will be produced in this way; *gravity is democratic*!
- The smallest black holes are also the hottest



Hawking Evaporation

- 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 the 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:

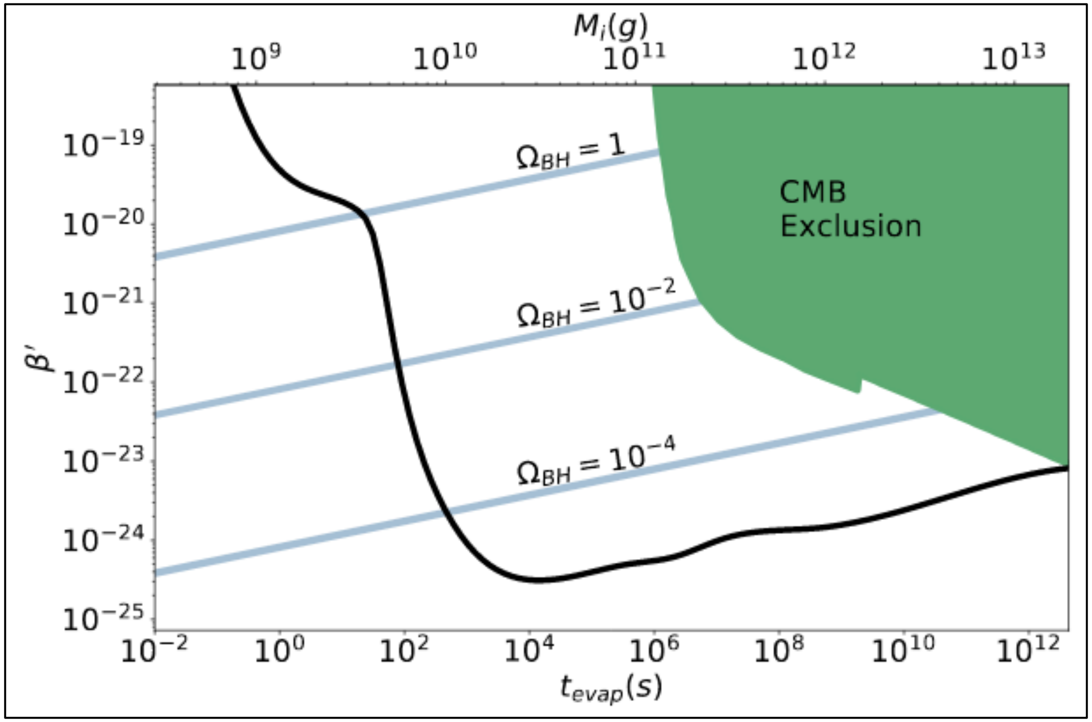
$$\tau \approx 1.3 \times 10^{-25}\,{\rm s\,g^{-3}} \int_0^{M_i} \frac{dM_{\rm BH} M_{\rm BH}^2}{g_{\star,H}(T_{\rm BH})} \approx 4.0 \times 10^{-4}\,{\rm s} \left(\frac{M_i}{10^8\,{\rm g}}\right)^3 \left(\frac{108}{g_{\star,H}(T_{\rm BH})}\right)$$

- Any primordial black holes with a mass of ~10^9-10^{12} grams will be evaporating *during* the formation of the light elements – ruled out by BBN
- Any black holes lighter than ~10^9 grams will be gone by the onset of BBN, and are thus almost entirely unconstrained

Constraints From the Light Element Abundances

Black holes can impact BBN in four primary ways:

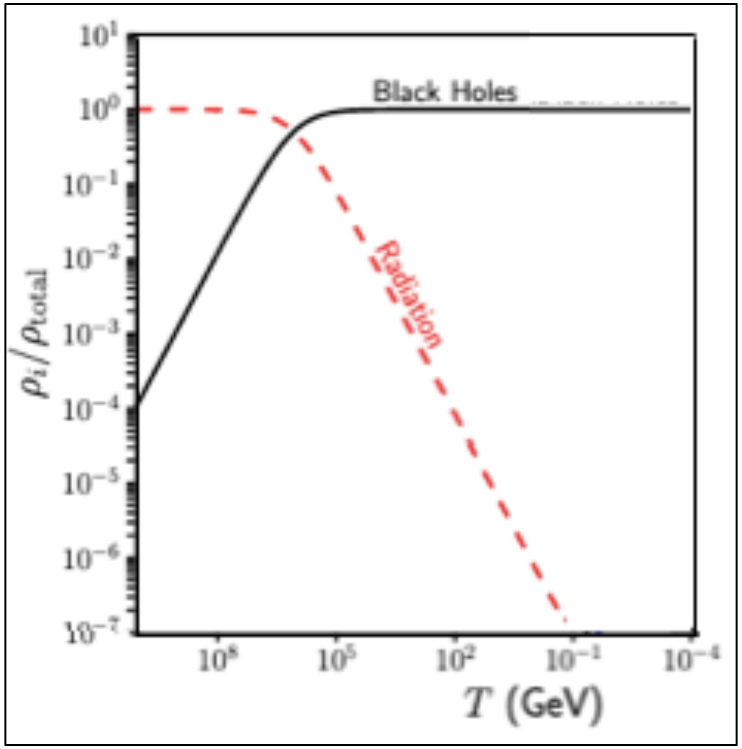
1) Increasing the expansion rate around T~MeV, increasing n/p and thus ^{4}He
2) Injecting hadrons and mesons, which increase n/p and thus ^{4}He
3) Photodissociation of ^{4}He, increasing D/H; important for T < 0.4 keV
4) Hadrodissociation of ^{4}He, increasing D/H; important for T > 0.4 keV



C. Keith et al.,
arXiv:2006.03608

Was the Early Universe Dominated by Black Holes?

- As the universe expands, the energy density of relativistic particles falls like $\rho_{rad}\ \boldsymbol{\alpha}\ a^{-4}$, 3 powers from geometrical dilution, and 1 power from redshifiting
- In contrast, black holes behave like particles of matter, and do not redshift, $\rho_{BH}\ \boldsymbol{\alpha}\ a^{-3}$
- As a result, the fraction of the total energy density in the form of black holes *grows* as the early universe expands, $\rho_{BH}/\rho_{rad}\ \boldsymbol{\alpha}\ a$
- 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



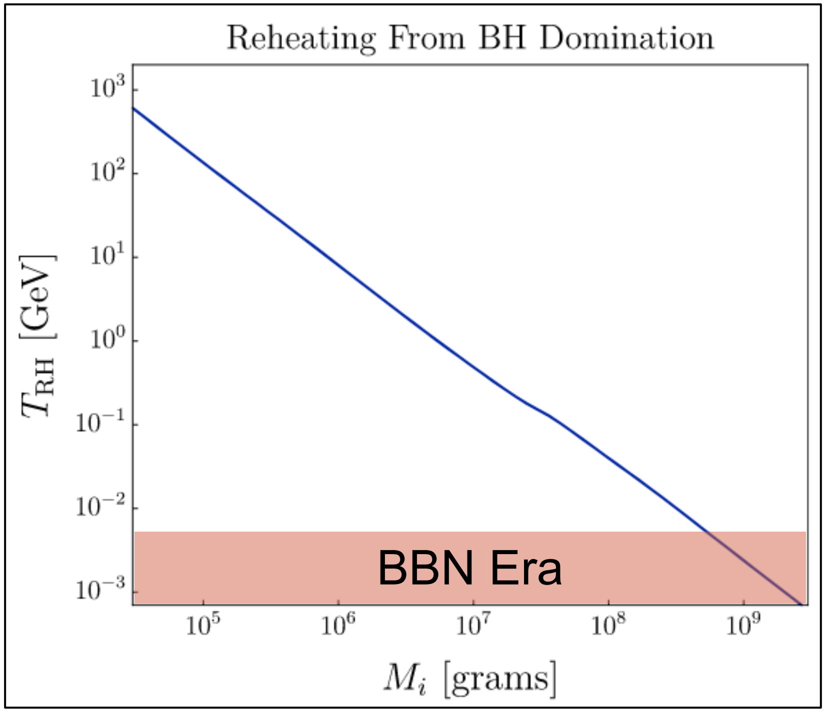
Was the Early Universe Dominated by Black Holes?

- 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:

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

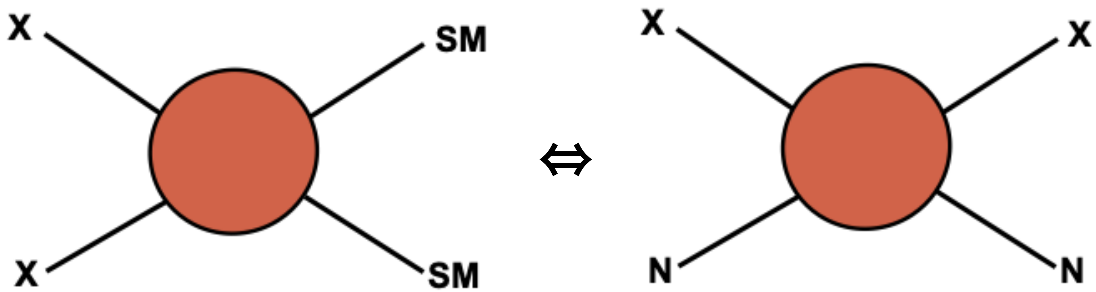
- Initial conditions (at the end of inflation) which include even a trace abundance of primordial black holes will naturally lead to an era in which the energy density is dominated by these objects

- 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

- Thermal relics with ~10 MeV-100 TeV masses and roughly weak-scale interactions (*ie*. WIMPs) have long been considered a particularly promising 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 – many WIMP models predict observable rates at direct detection experiments



- 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

If Not WIMPs, Then What?

- Although WIMPs remain a viable possibility, the lack of signals in direct detection experiments and at the LHC provide us with motivation to consider other ways in which the dark matter may have been created in the early universe; especially those that could generate a population of very feebly interacting dark matter particles

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- Some well-known examples include:

  -Misalignment production (axions, etc.)

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

  -Production via neutrino oscillations (with a large lepton number asymmetry)

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

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- One 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

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- 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

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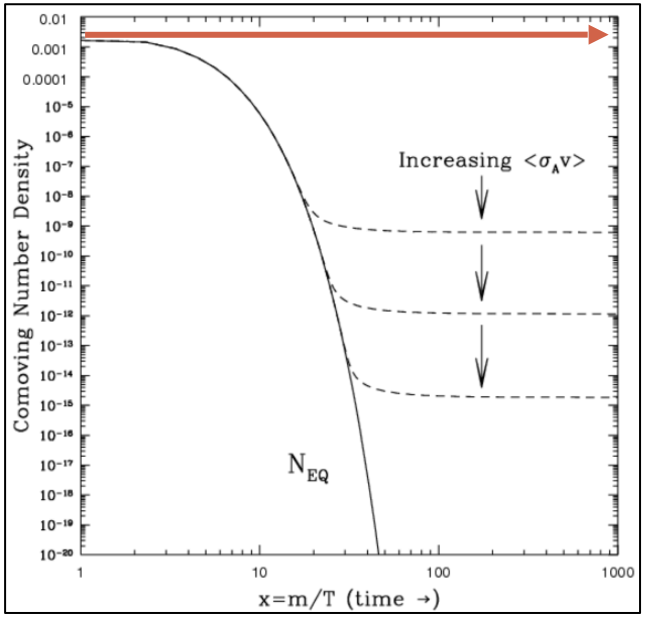
- This black hole will radiate *all* kinds of particles that are lighter than ~100 TeV, regardless of their electric charge, QCD color, or any other quantum numbers
- This includes any particles lighter than ~100 TeV that we have *not discovered yet!* – axions, hidden photons, right-handed neutrinos, gravitons, supersymmetric particles, *etc*.
- Black holes are ideal factories of exotic 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

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

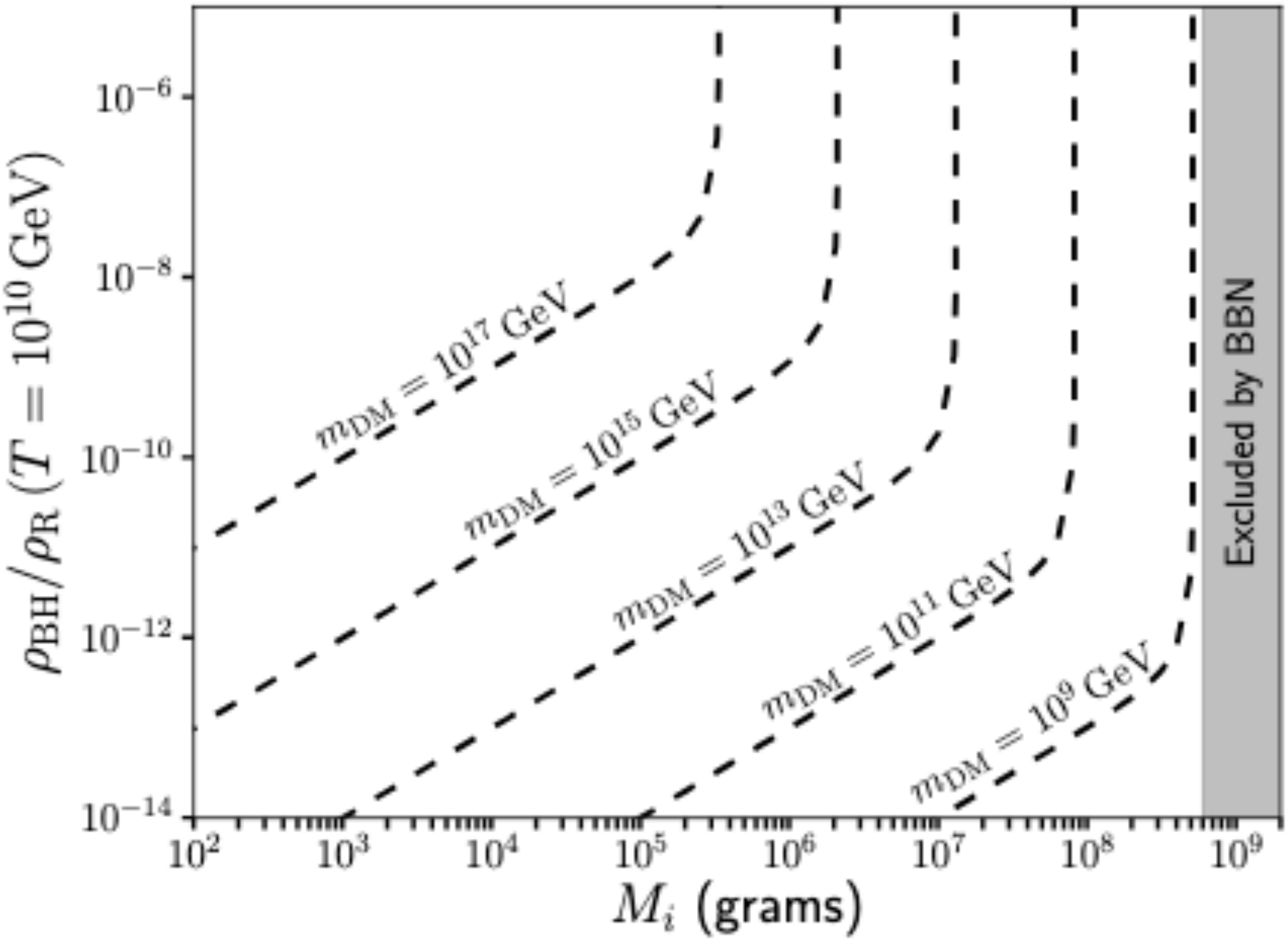
- This situation is similar to that of a stable particle species that was at an equilibrium abundance in the early universe, but with a negligible annihilation cross section (and no other means of being depleted)
- The problem is not how to make the dark matter through Hawking evaporation, but rather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



Dark Matter From Hawking Evaporation

- To evade this problem, one can 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 ~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 ~6×10^{10} GeV, at which time the black hole's mass has been reduced to ~2×10^2 grams
- As a result, the total output into these supermassive particles is suppressed by a factor of ~$T_{BH,I} / m_{DM} \sim 10^5 / 10^{11} \sim 10^{-6}$
- After accounting for this, we find that a black hole dominated era will result in the following abundance of dark matter particles:

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



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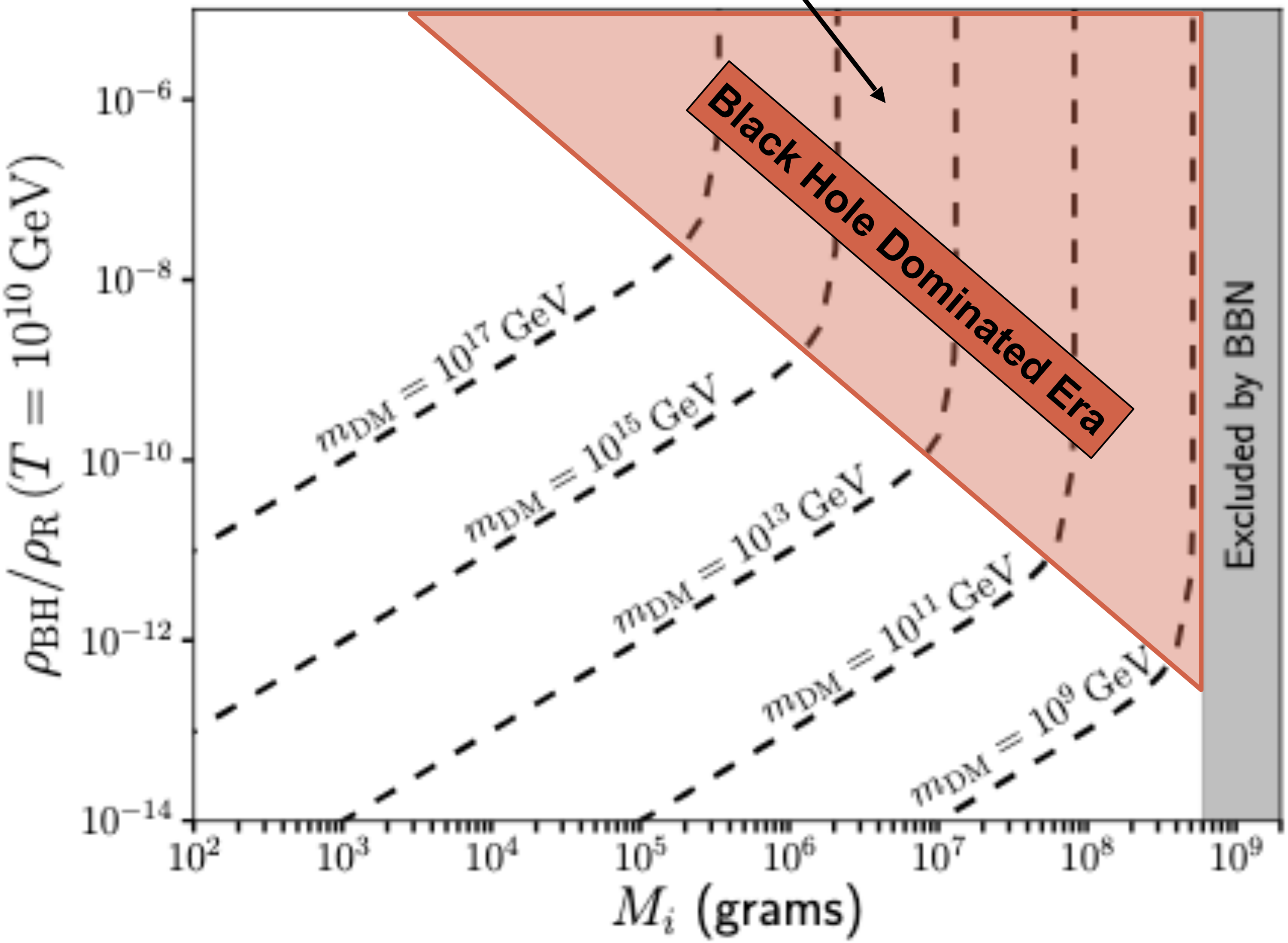

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$$\Omega_{\rm DM} h^2 \approx 0.1 \left(\frac{f_i(10^{10}\,{\rm GeV})}{8\times 10^{-14}}\right)\left(\frac{g_{{\rm DM},H}}{4}\right)\left(\frac{10^9\,{\rm GeV}}{m_{\rm DM}}\right) \times \left(\frac{10^8\,{\rm g}}{M_i}\right)$$

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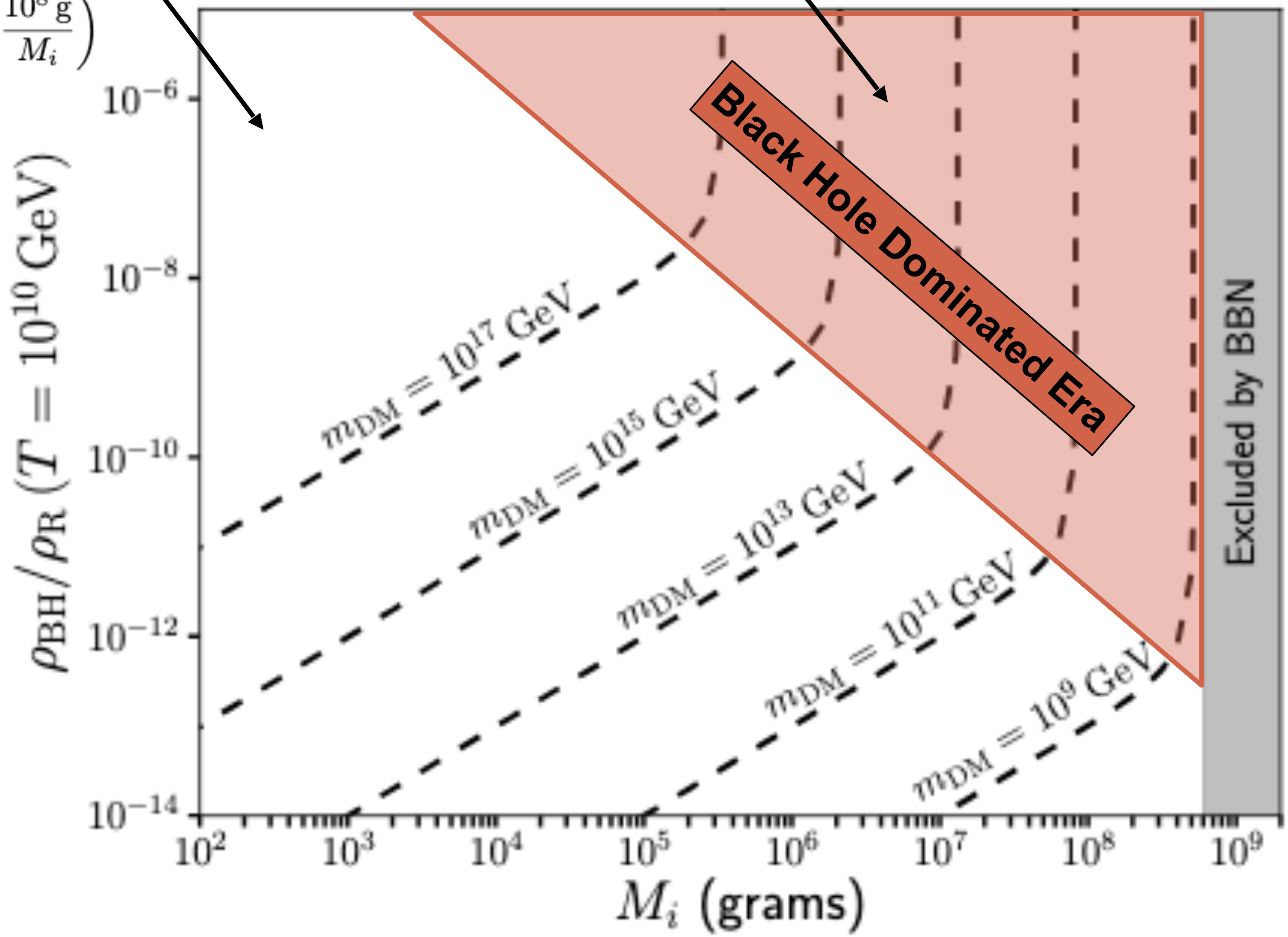

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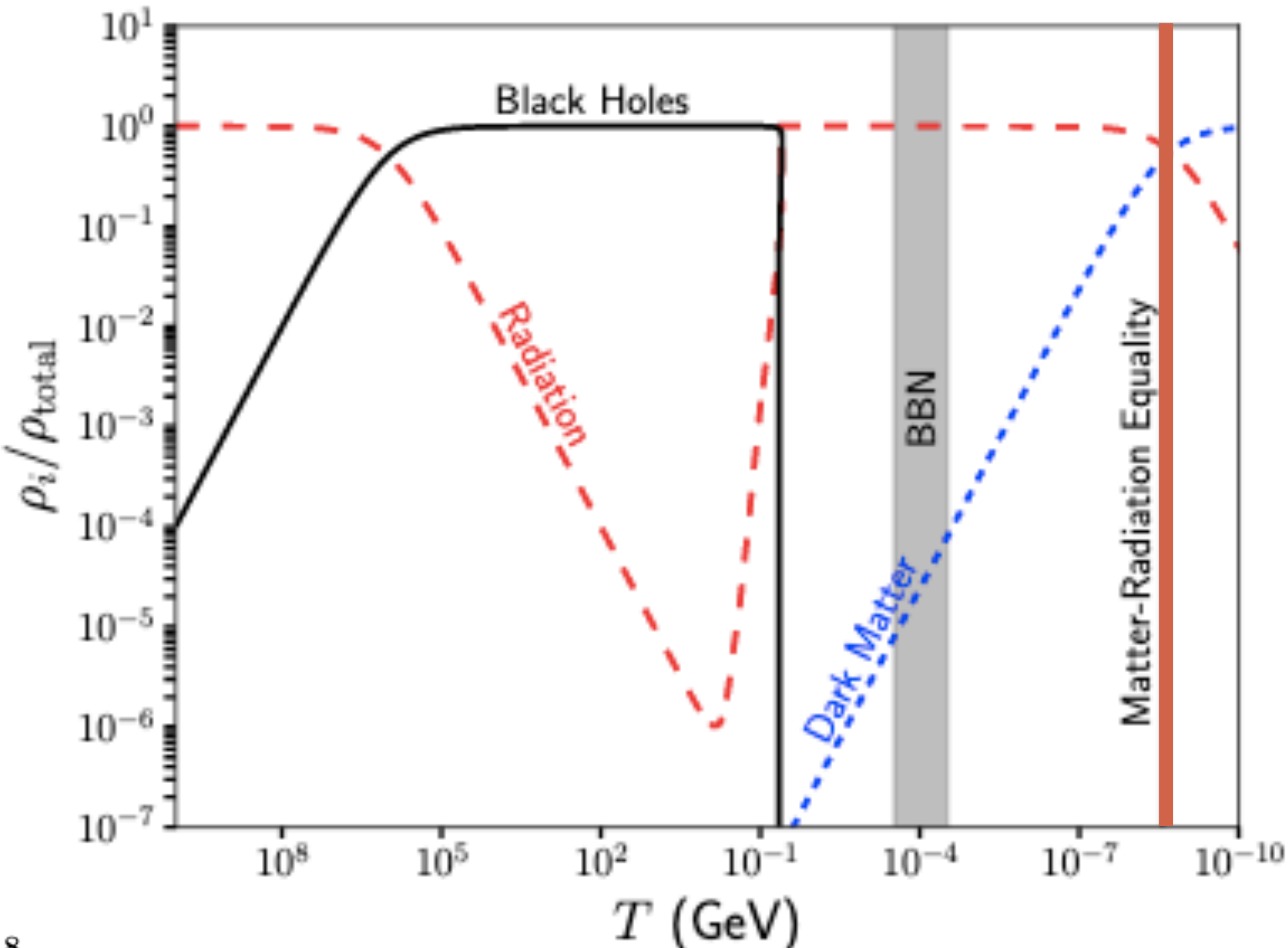
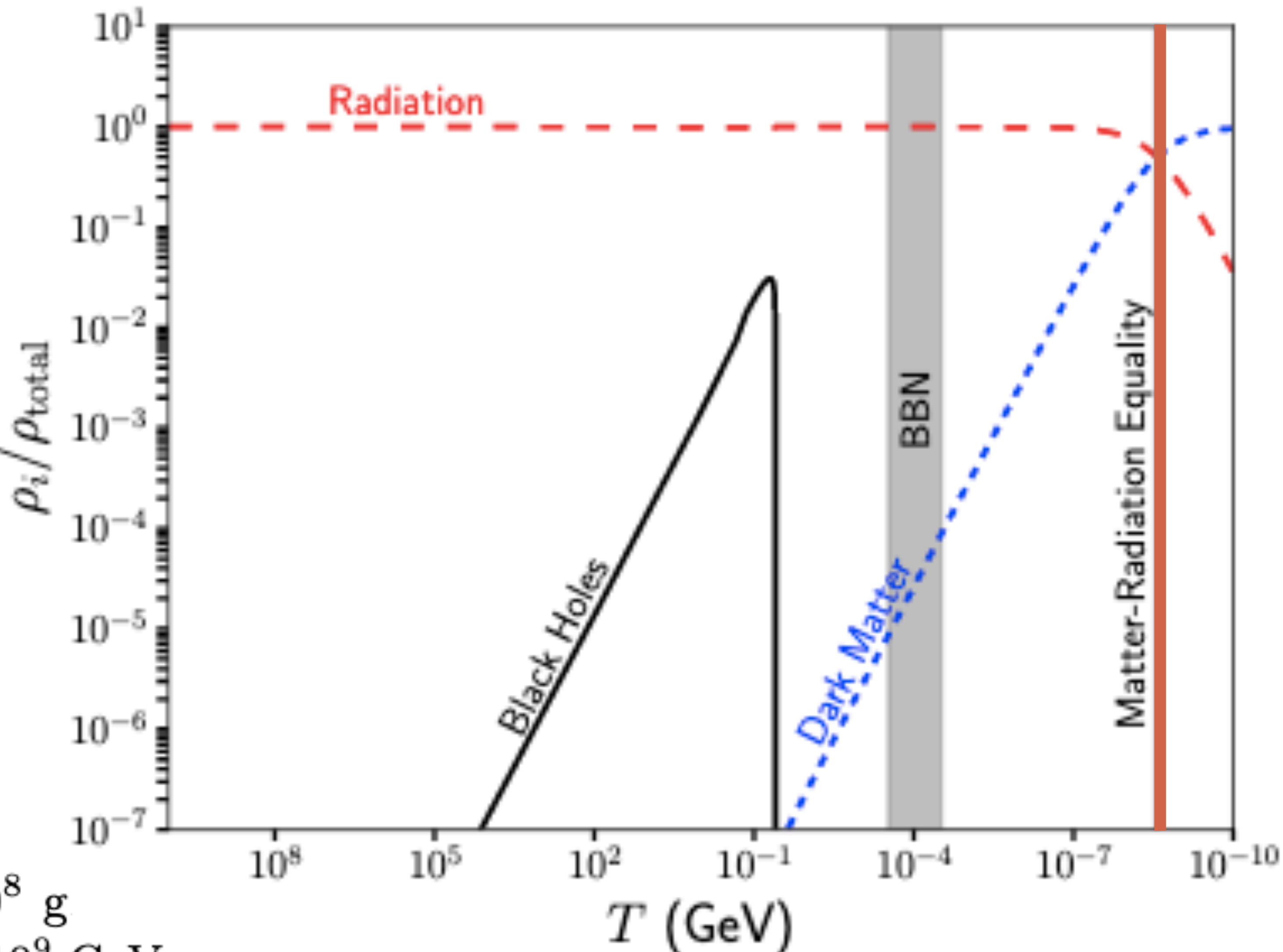
Example with a black hole dominated era



$M_i = 10^8$ g

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

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

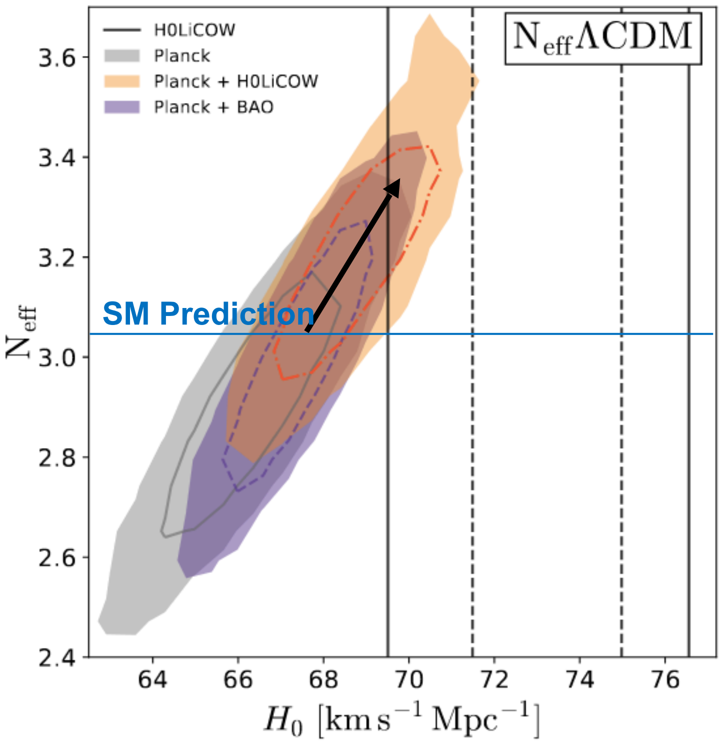
- Within this context, Planck-scale relics could be an attractive candidate for dark matter

Motivation #2: 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 #2: 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 $\Delta N_{eff} \sim 0.1\text{-}0.3$ approximately minimizes this tension



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

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 $\Delta N_{eff} \sim 0.3$

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 feebly 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

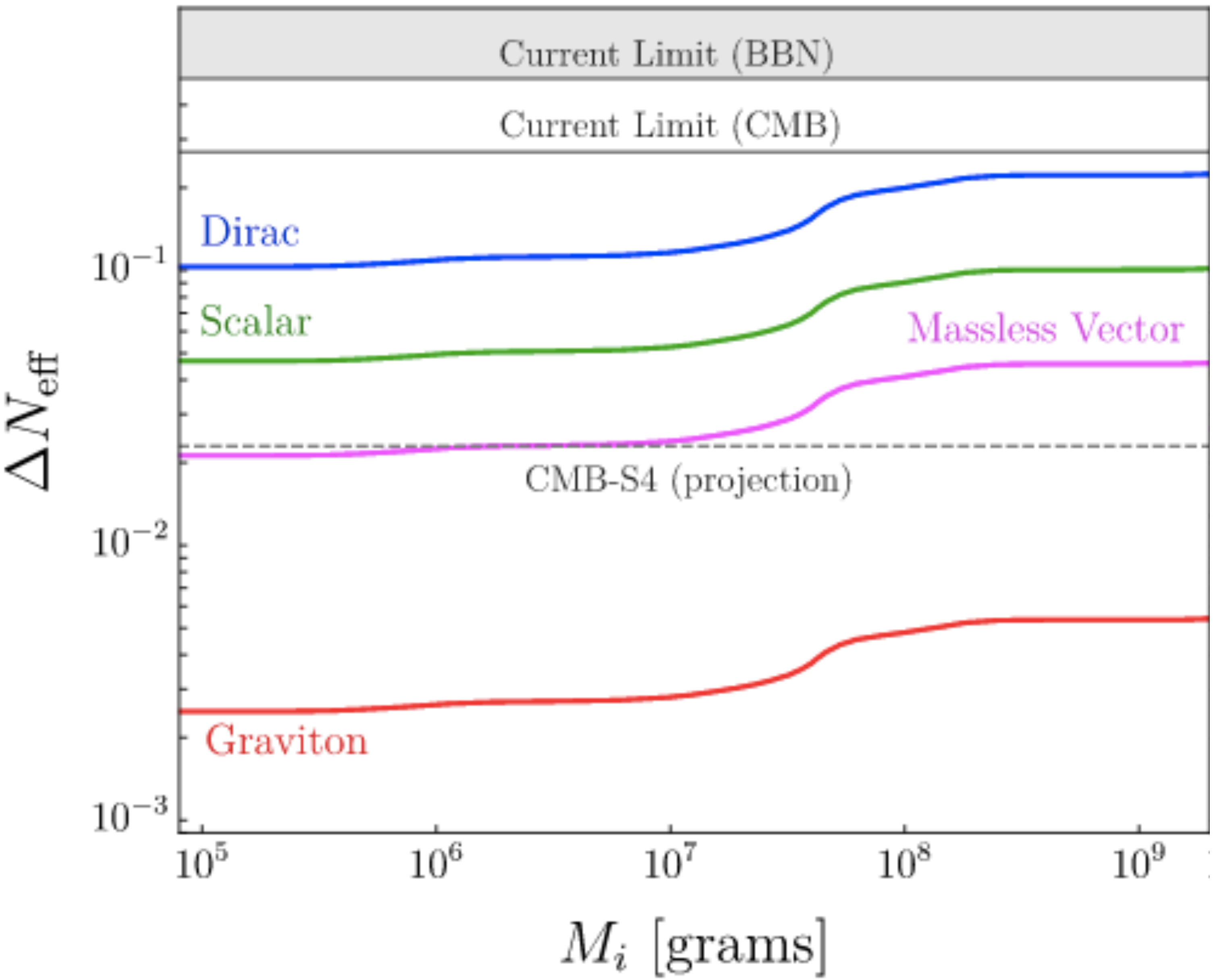
Dark Radiation From Hawking Evaporation

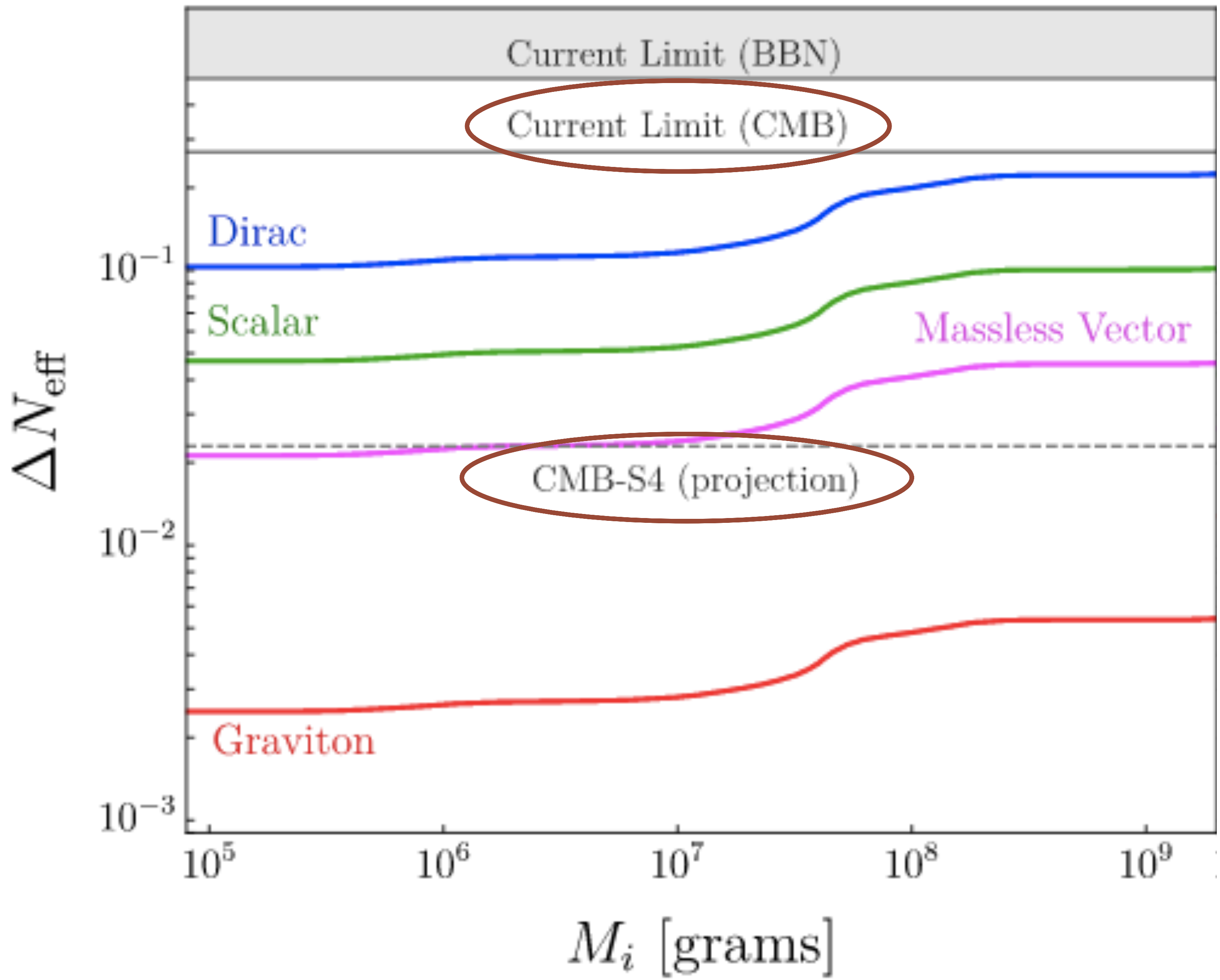
- Immediately after a black hole dominated era, the fraction of the energy density in an exotic light particle species will be given by their (greybody factor-weighted) degrees-of-freedom, $g_{\mathrm{DR},H}/g_{\star,H}$.
- After accounting for SM entropy dumps, we arrive at:

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

- 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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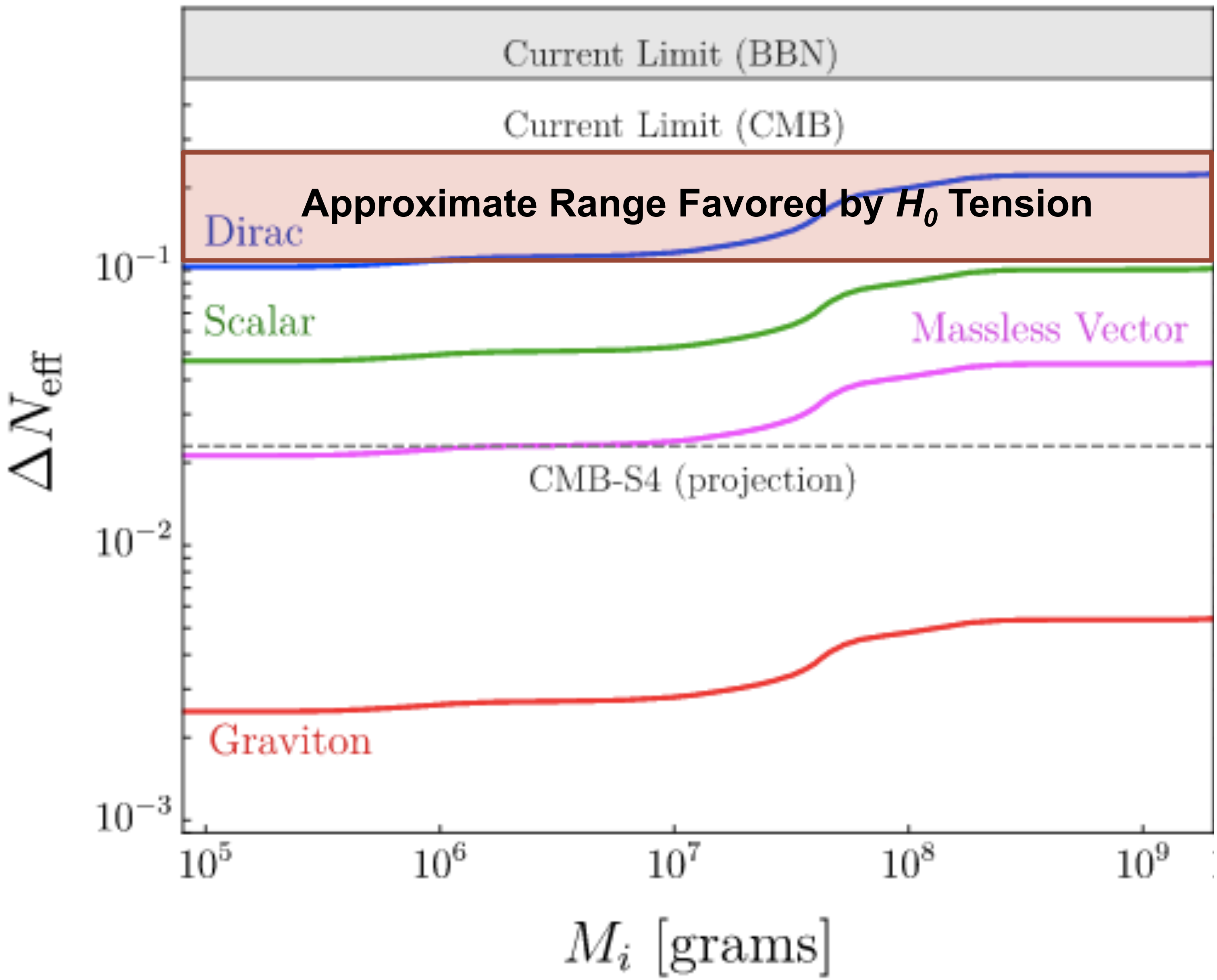
M_i [grams]


Current Limit (BBN)
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Approximate Range Favored by H_0 Tension
Dirac
Scalar
Massless Vector
CMB-S4 (projection)
Graviton
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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 α = 2.7 (3.15) for bosonic (fermionic) dark radiation

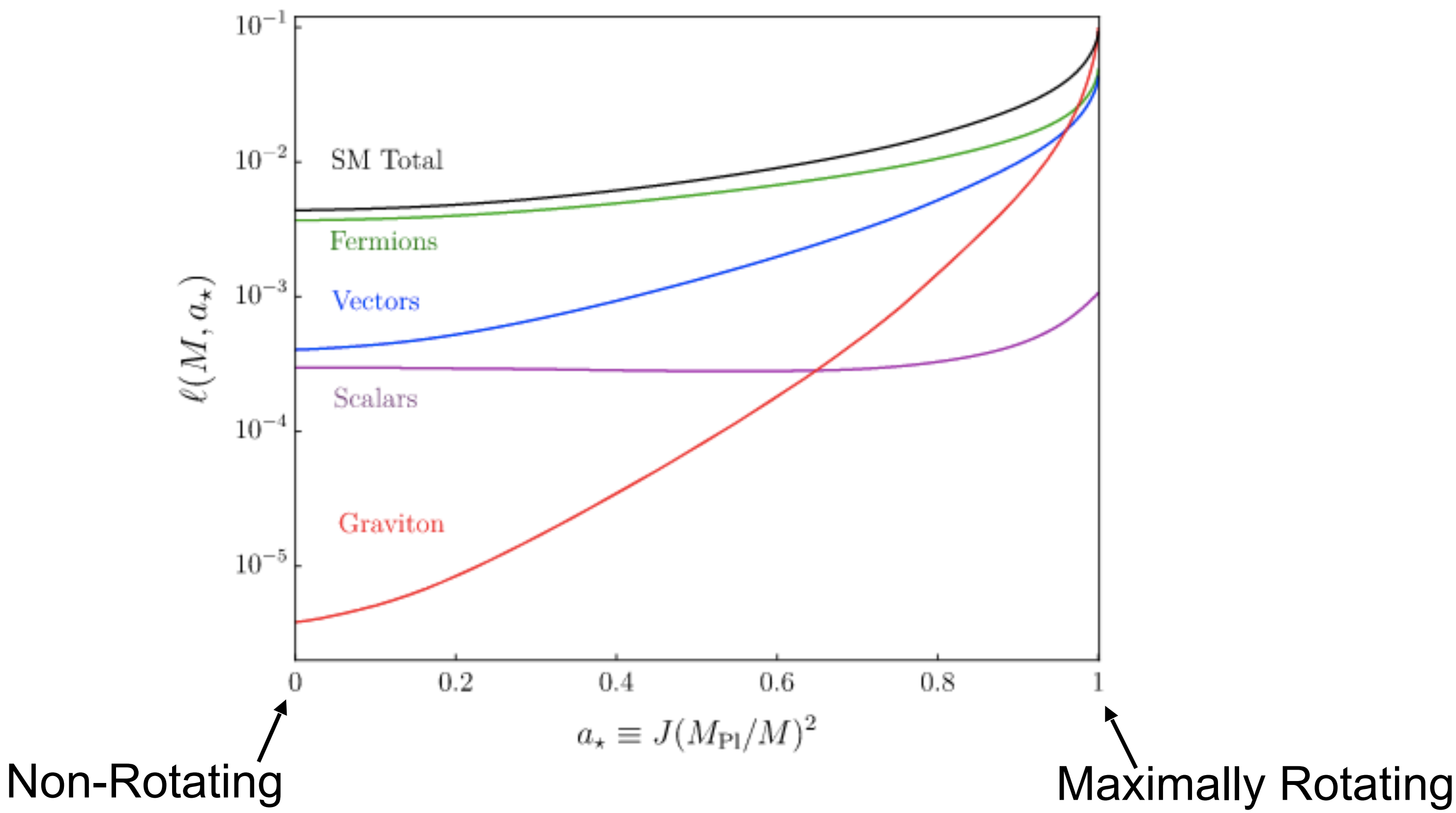
- Integrating over the lifetime of the black holes, we arrive at a slightly higher value, $\sim 5.5\,{\rm MeV} \times (M_i/10^8\,{\rm g})^{1/2}$.
- In contrast to thermally produced dark radiation (which must be lighter than ~eV), dark radiation that is produced through Hawking evaporation can consist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

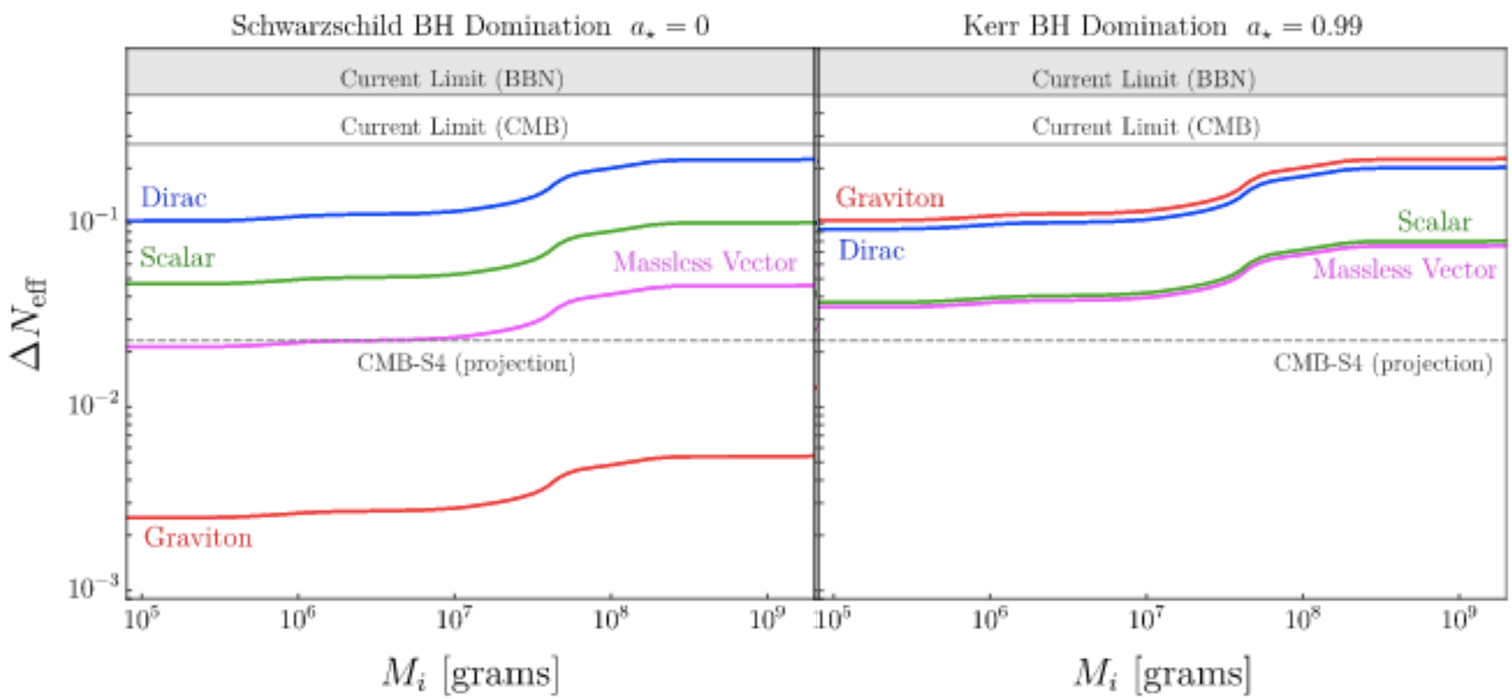
Hawking Radiation From Rotating Black Holes

- 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:



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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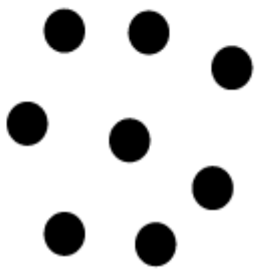
$a_\star \sim 0$



1.BH formation

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

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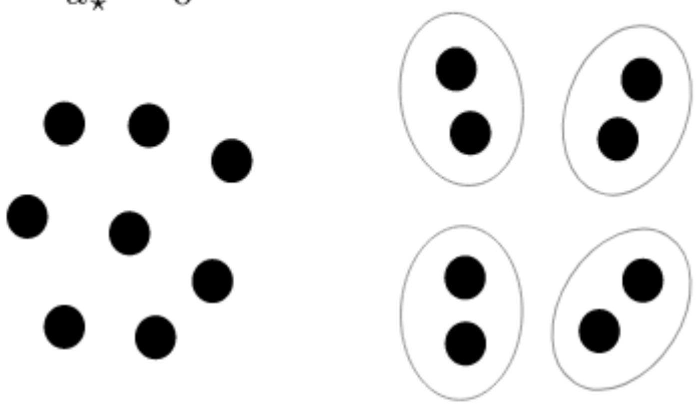

1.BH formation
$\rho_{\rm BH} \ll \rho_{\rm tot}$

2. Binary Capture
$\Gamma_{\rm C} \sim H$

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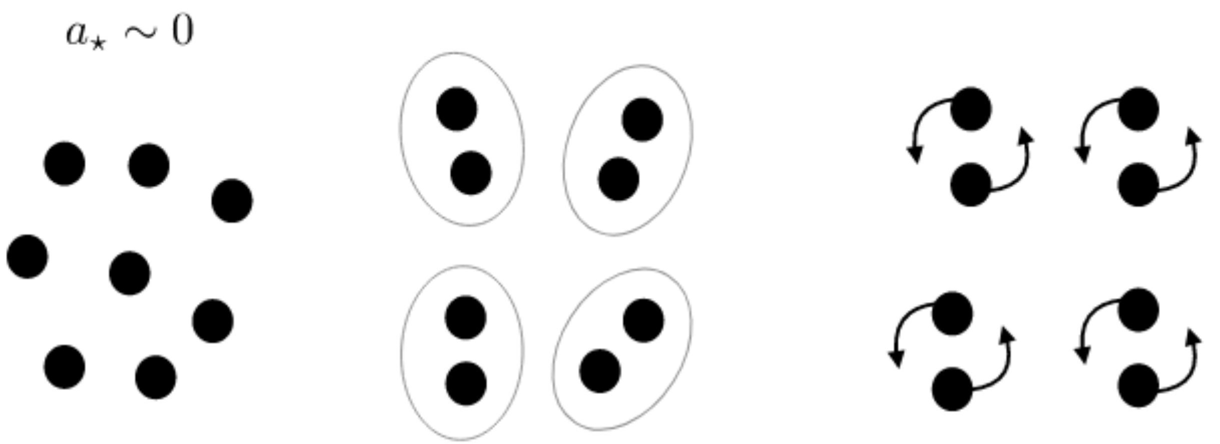

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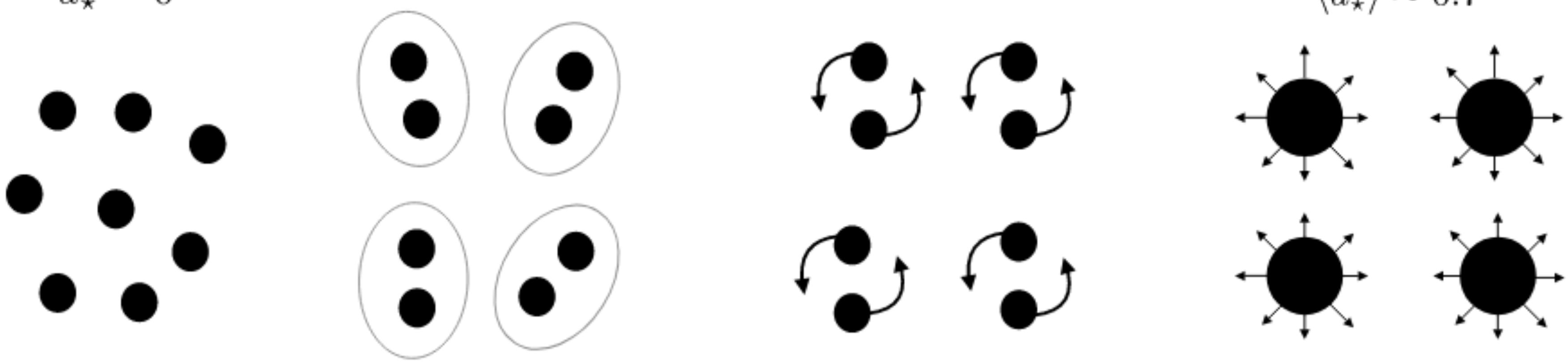
$\Gamma_{\rm C} \sim H$

3. Mergers
$\rho_{\rm BH} \sim \rho_{\rm tot}$
$\rho_{\rm GW} \rightarrow \Delta N_{\rm eff,GW}$

How Might Primordial Black Holes Come to be Rapidly Spinning?

$a_\star \sim 0$

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



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

3. Mergers
$\rho_{\rm BH} \sim \rho_{\rm tot}$
$\rho_{\rm GW} \rightarrow \Delta N_{\rm eff,GW}$

4. Hawking Radiation
$\rho_{\rm BH} \rightarrow \rho_R + \rho_{\rm G} + \cdots$
$\Delta N_{\rm eff,G}$

Gravitational Capture

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

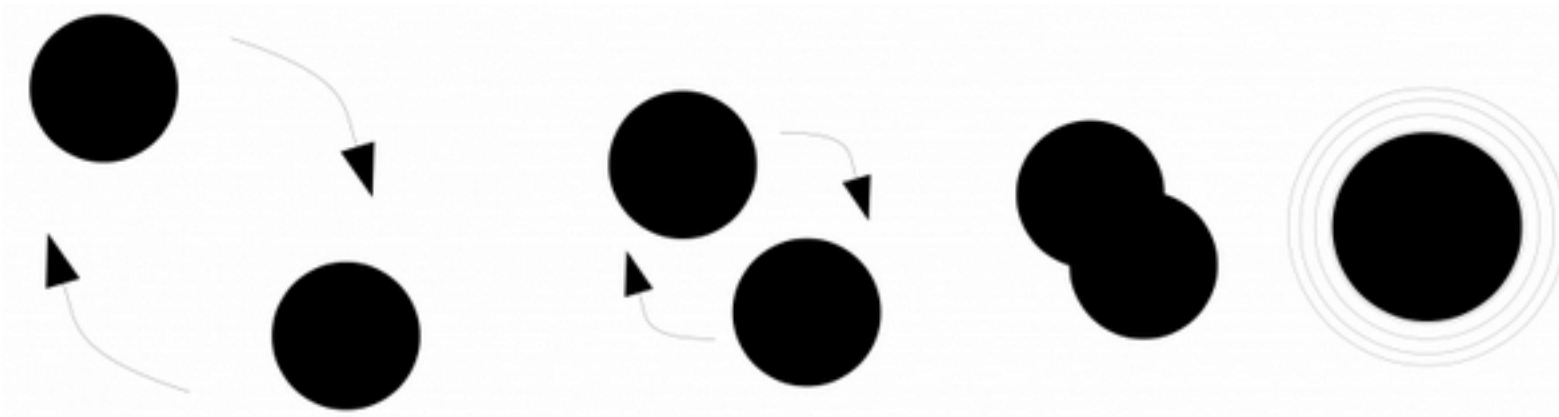
$$\sigma_{\rm C} = \frac{2\pi}{M_{\rm P}^4}\left[\left(\frac{85\pi}{6\sqrt{2}}\right)^2 \frac{(M_1+M_2)^{10}(M_1M_2)^2}{v^{18}}\right]^{1/7}$$

- 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

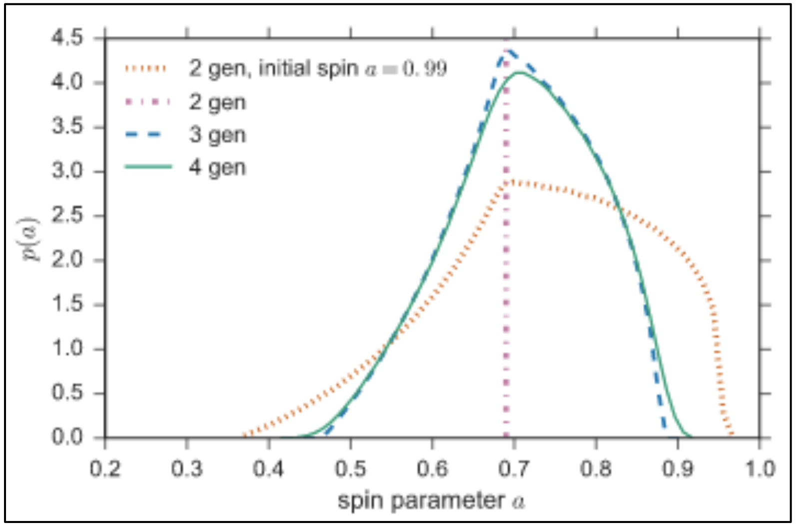
- This situation persists until Γ_C falls below the rate of Hubble expansion

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

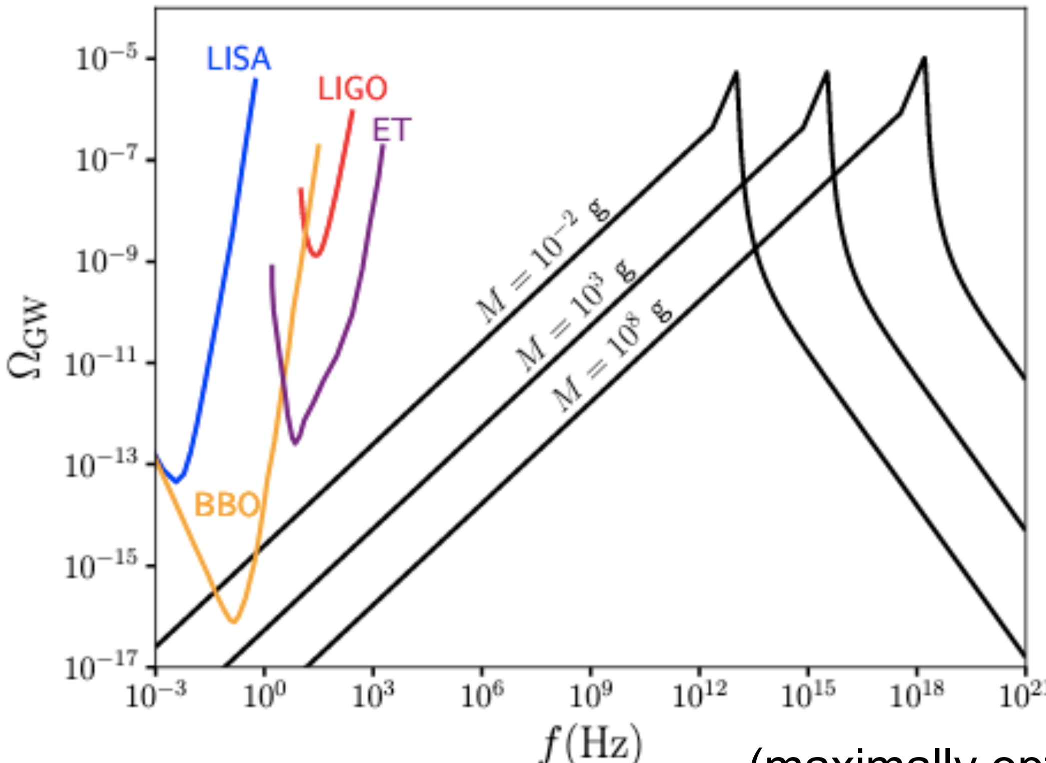


Fishbach, Holz, Farr, arXiv:1703.06869

Potentially Observable Signals

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

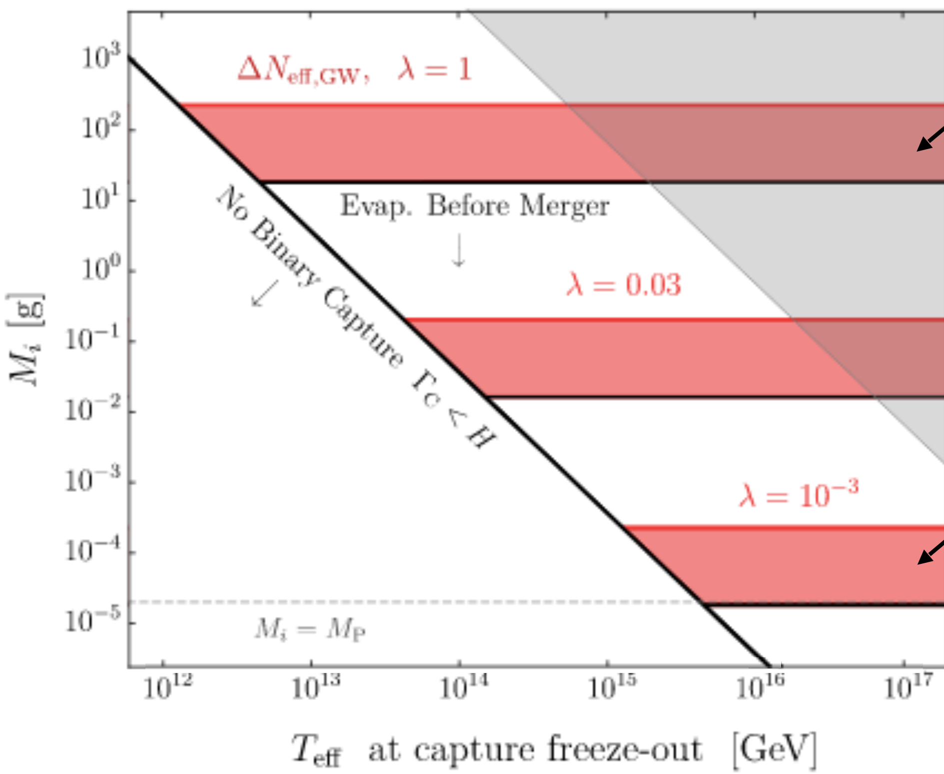


(maximally optimistic case shown; mergers just prior to evaporation)

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 address the Hubble tension, and be within the reach of upcoming CMB experiments



Observable band, loosely bound orbits

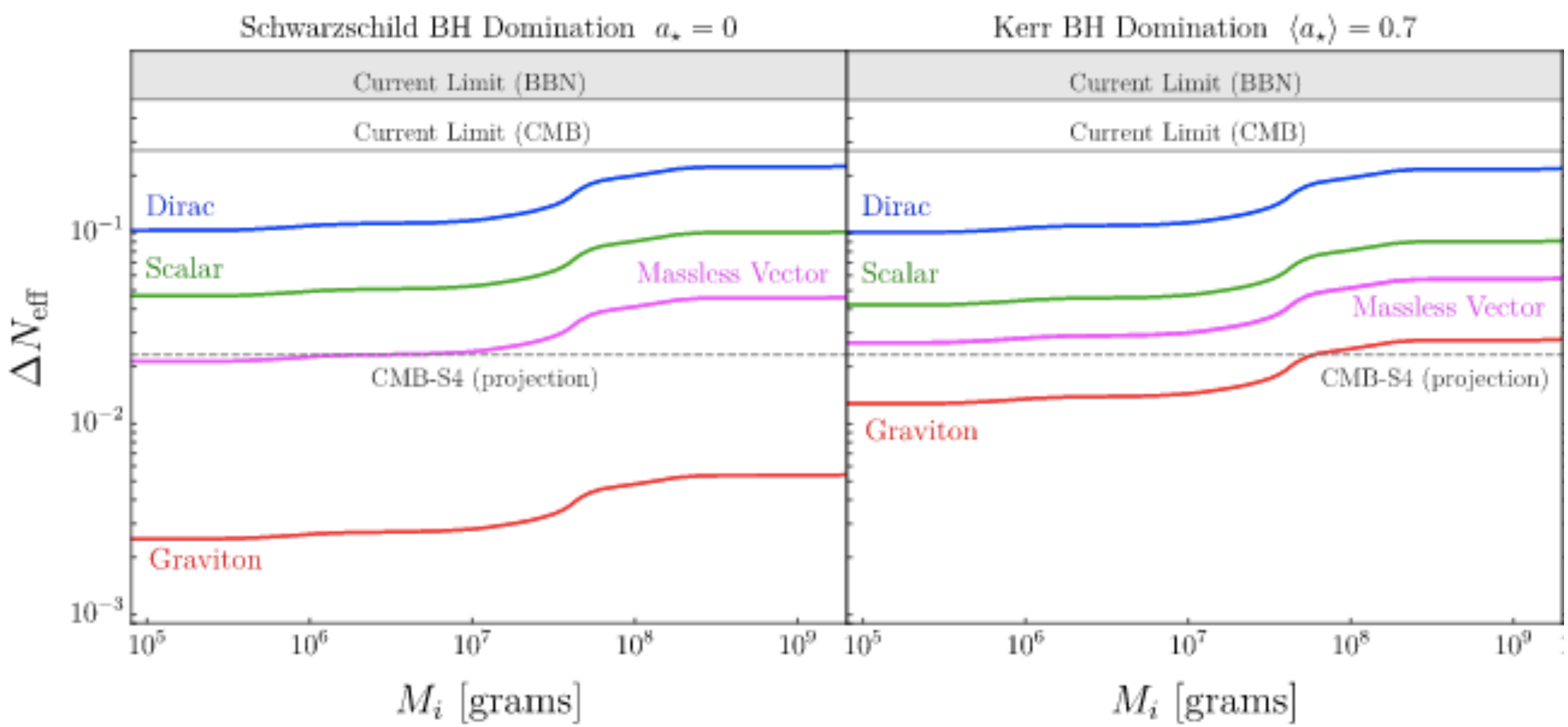
Observable band, tightly bound orbits

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:

$T_G \sim$ eV - keV, $T_{CMB} \sim T_{C\nu B} \sim 10^{-3}$ eV – the "*Hot Graviton Background*"



Summary: A Few Key Takeaways

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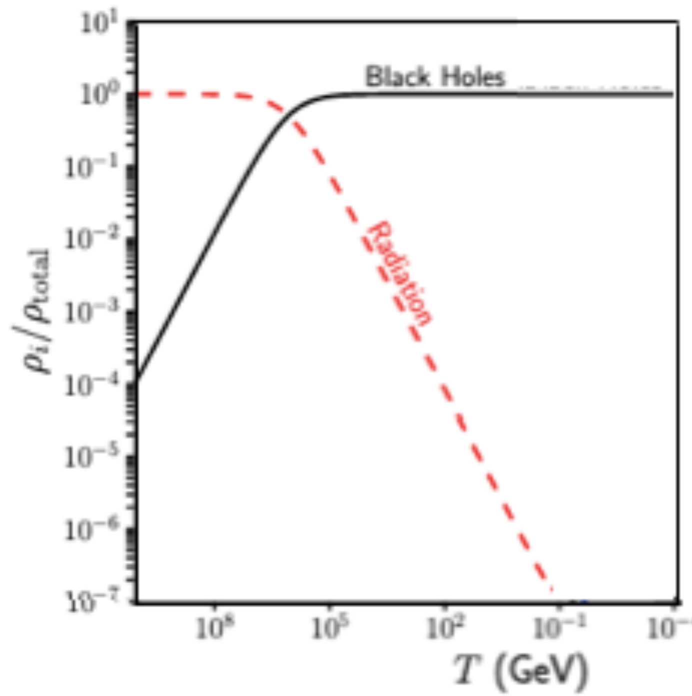
1) If black holes made up even a trace fraction of the total energy density after inflation, this fraction will increase as the universe expands, ultimately dominating the total energy density if the following condition is met:

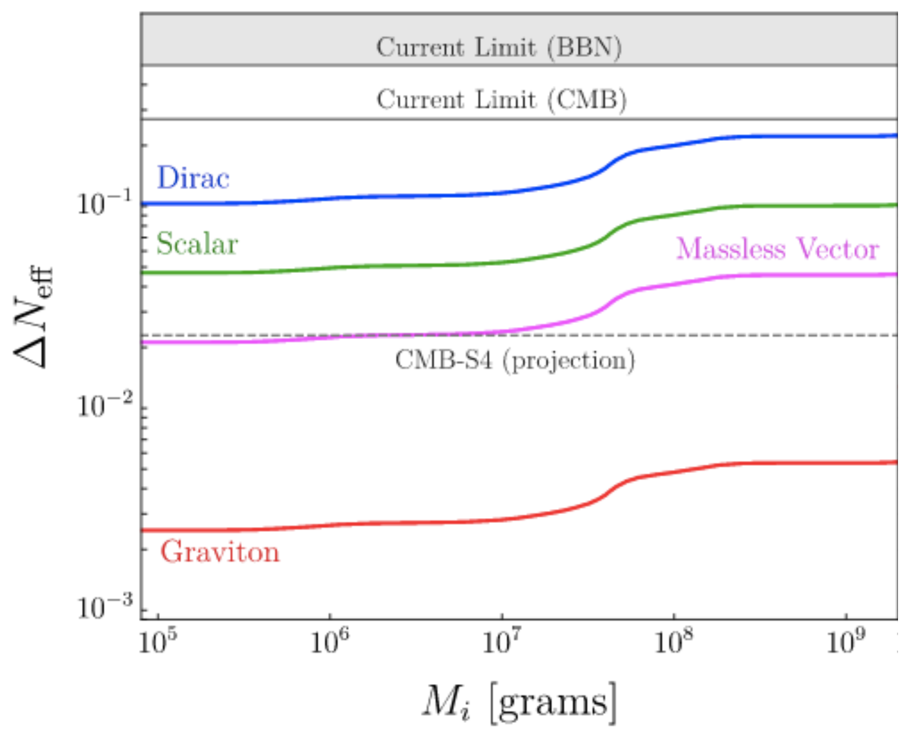
$$f_i \equiv \frac{\rho_{\mathrm{BH},i}}{\rho_{R,i}} \gtrsim 4 \times 10^{-12} \left(\frac{10^{10}\,\mathrm{GeV}}{T_i}\right) \left(\frac{10^8\,\mathrm{g}}{M_i}\right)^{3/2}$$



Summary: A Few Key Takeaways

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

Primordial black holes provide an attractive way to resolve the Hubble tension



Summary: A Few Key Takeaways

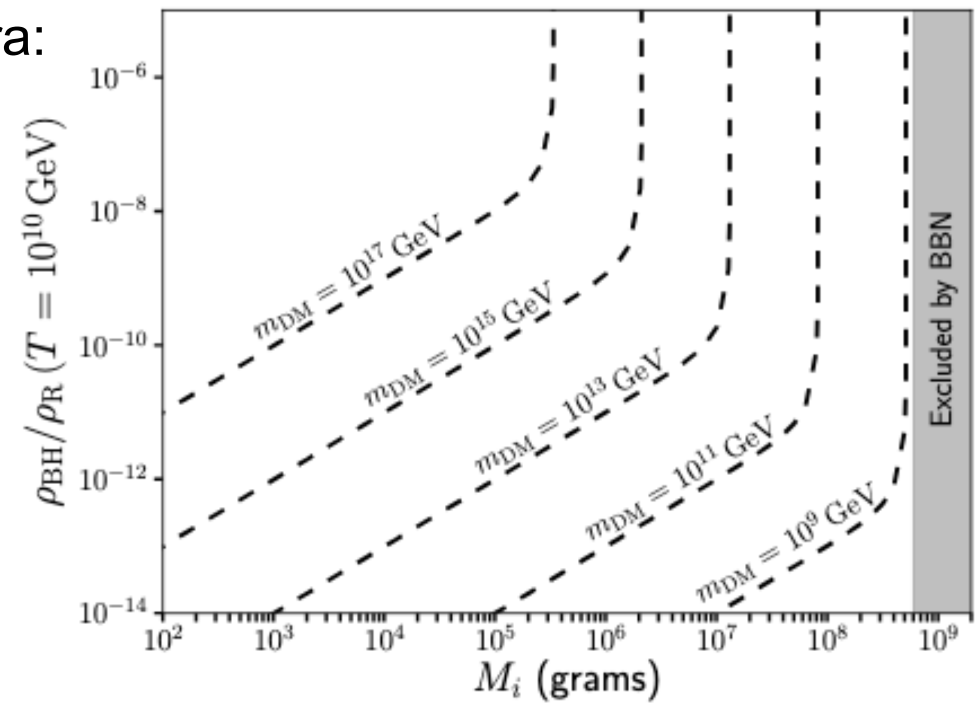
3) Hawking radiation could easily produce the measured abundance of dark matter

If there was a black hole dominated era:

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

Without a black hole dominated era:

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



Summary: A Few Key Takeaways

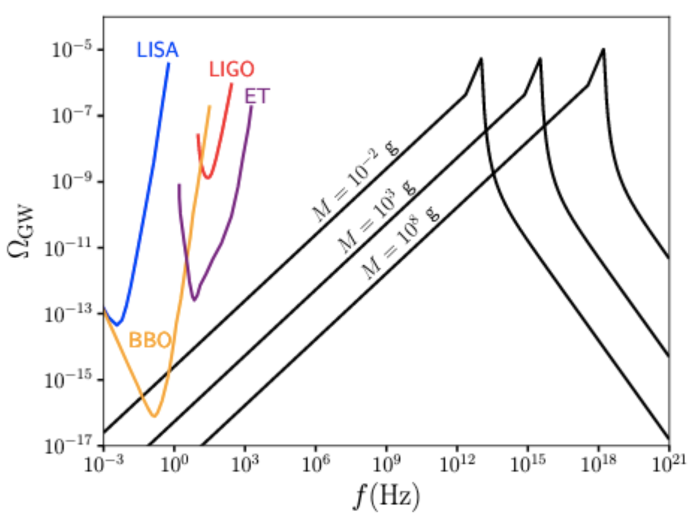
4) Mergers in the early universe could have left these black holes with appreciable angular momentum – Kerr black holes

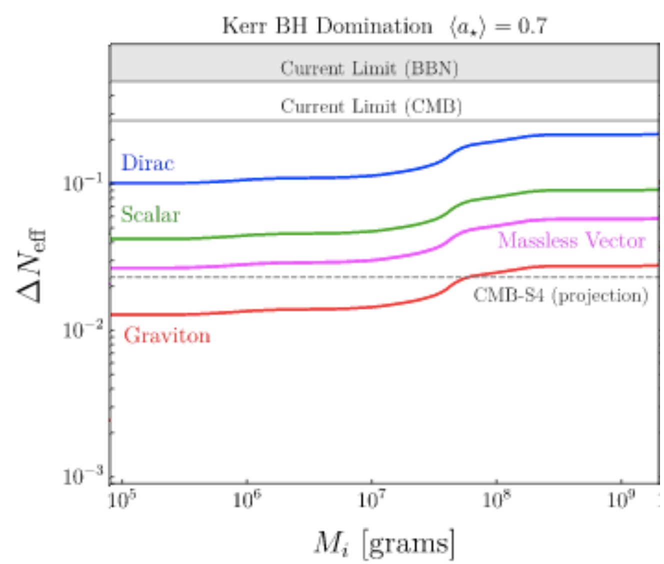
Several potentially observable consequences:

-A stochastic background of high-frequency gravitational waves

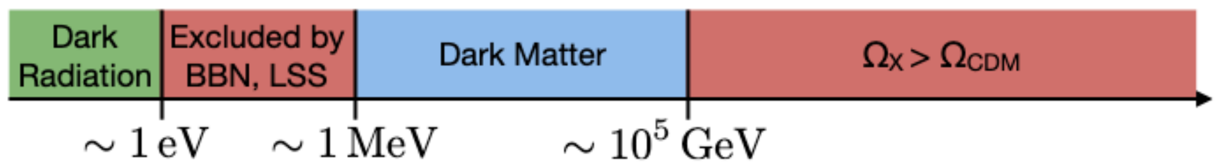
-These gravitational waves are dark radiation, with ΔN_{eff} as large as ~0.3

-These Kerr black holes preferentially radiate high spin particles, leading to the production of a "*hot graviton background*"

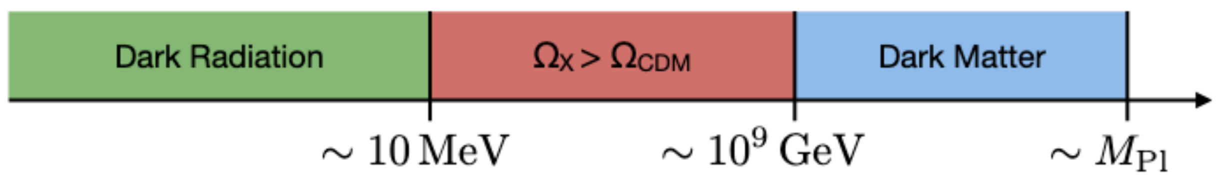


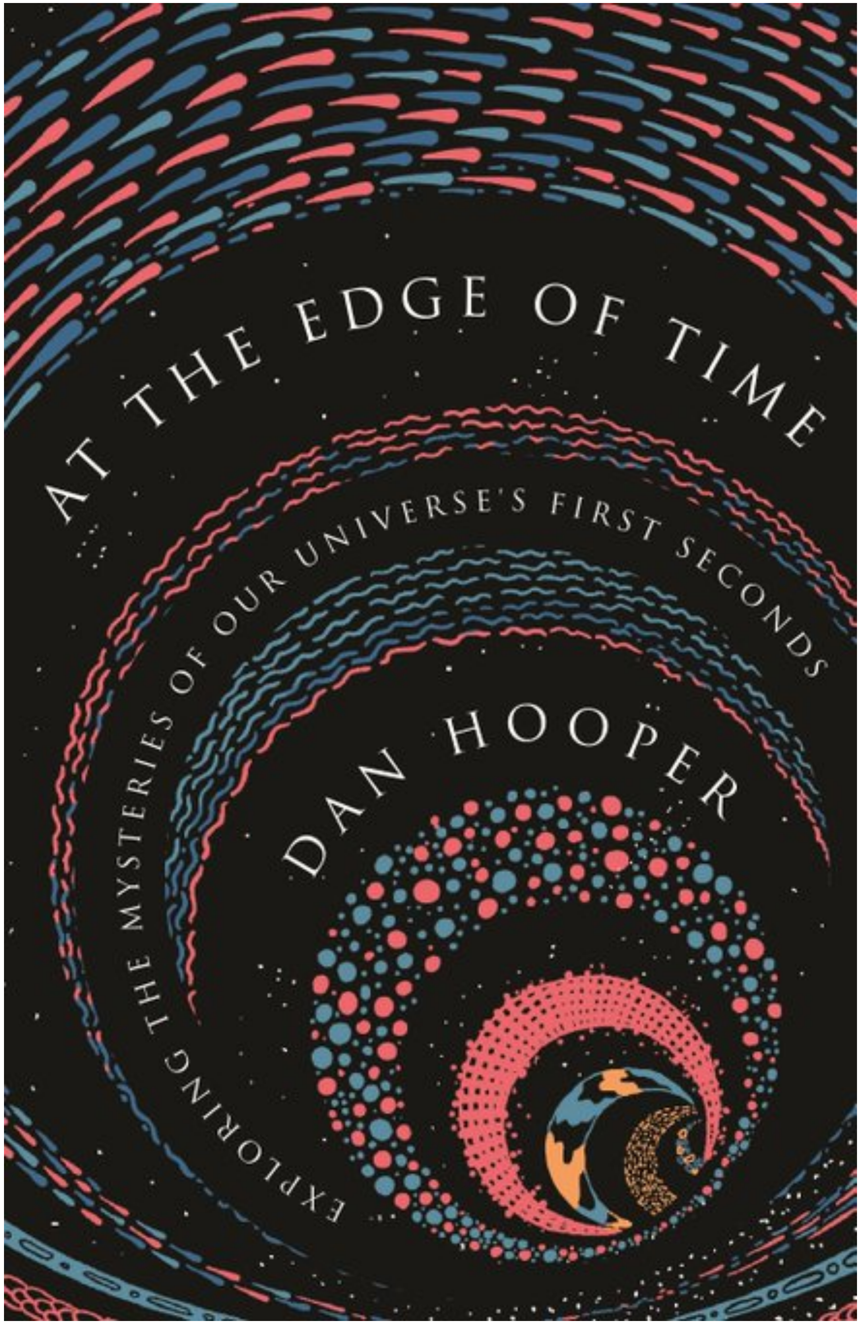


Thermal Relic



Hawking Radiation




AT THE EDGE OF TIME
EXPLORING THE MYSTERIES OF OUR UNIVERSE'S FIRST SECONDS
DAN HOOPER


WHY THIS UNIVERSE?

Motivation #3: The Baryon Asymmetry

- In GUT baryogenesis, very massive gauge or Higgs bosons are produced in the early universe which generate the baryon asymmetry through their *B*, *C* and *CP* violating decays
- Proton decay constraints generally require these baryon number violating particles to be very heavy, typically $\sim 10^{12-16}$ GeV
- Constraints from BICEP2/Keck on the energy scale of inflation, $V_{Inf} < (1.6 \times 10^{16}\ \mathrm{GeV})^4$, combined with constraints on the shape of the inflationary potential, suggest that the universe was reheated to only $\sim 10^9$-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

The presence of black holes in the early universe could impact GUT baryogenesis is several potentially important ways:

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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 doesn't require a high reheating temperature

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2) **Evade sphaleron washout** – Black holes heavier than ~$3x10^5$ 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