Topics in Primordial Black Hole Physics - Formation, Radiation, and Evaporation

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The Effects of Primordial Black Holes on Dark Matter Models

Paolo Gondolo, Pearl Sandick, Barmak Shams Es Haghi

arXiv:2009.02424 (PRD 102 9)

Precision Calculation of Dark Radiation from Spinning Primordial Black Holes and Early Matter Dominated Eras

Alexandre Arbey, Jérémy Auffinger, Pearl Sandick, Barmak Shams Es Haghi, Kuver Sinha

arXiv:2104.04051 (PRD 103 12)

PBH Formation

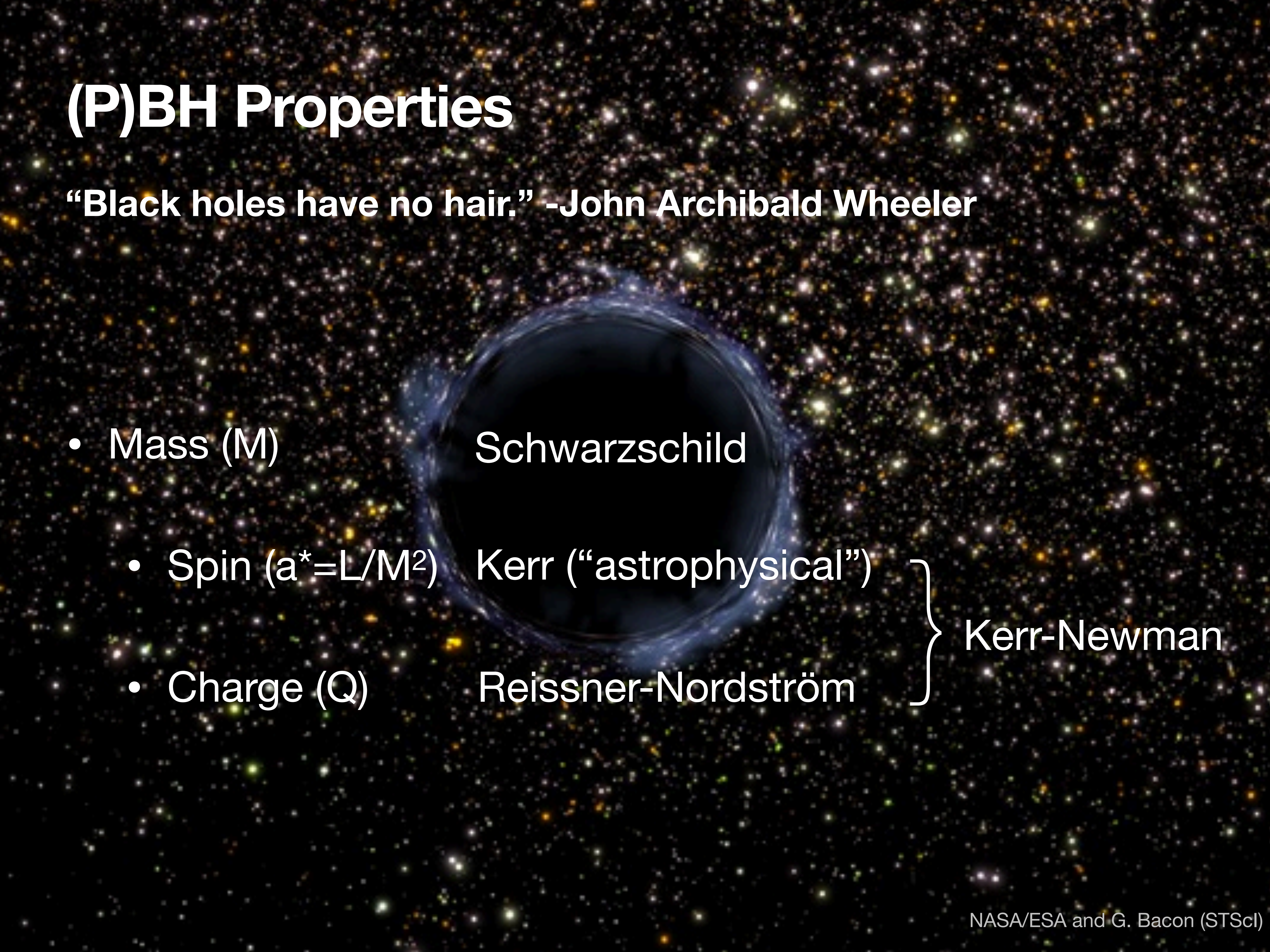
- Primordial Black Holes (PBHs) formed in the very early universe
- Proposed in the 60's, studied extensively by Hawking and others in the 70s
- Various mechanisms:
    - collapse of large density perturbations
    - collapse of cosmic string loops
    - bubble collisions
    - …
- Can happen during a radiation- or (early) matter-dominated era
- Possible that PBHs themselves come to dominate the energy density of the universe

- Formation requires increased energy density at early times → connection between PBH mass and horizon mass at formation

$$M \sim \frac{c^3\, t}{G} \sim 10^{15} \left(\frac{t}{10^{-23}\ \mathrm{s}}\right) \mathrm{g}.$$

    - Planck time → 10^{-5} g (Planck mass)
    - 1 second → 10^{5} m_sun
- Formation over a long time period means a range of masses at formation.
- Dimensionless initial energy density in PBHs (at formation time t_i):

$$\beta(M) \equiv \frac{M\, n_{\mathrm{PBH}}(t_i)}{\rho(t_i)}$$



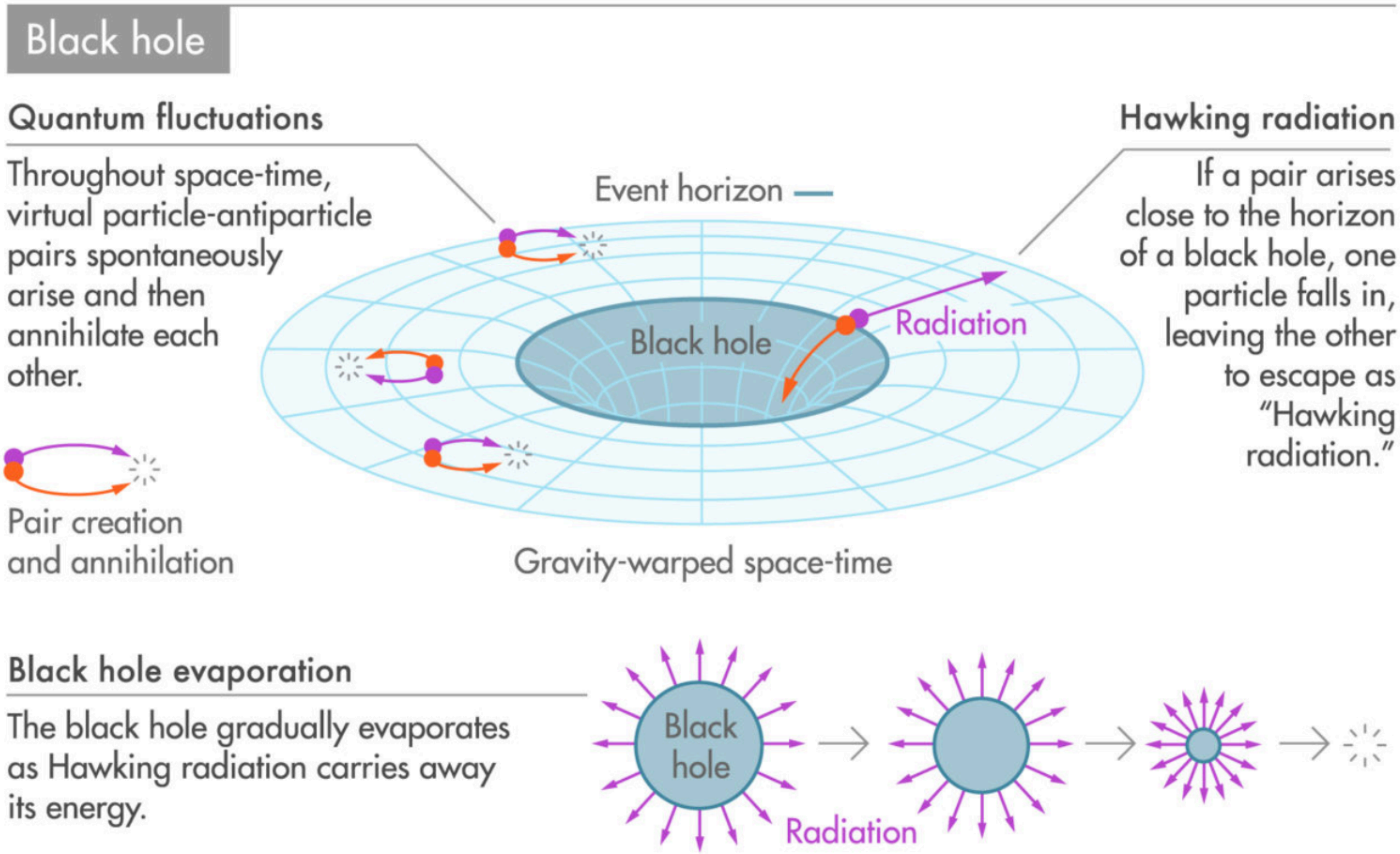
(P)BH Properties

“Black holes have no hair.” -John Archibald Wheeler

• Mass (M)	Schwarzschild	
• Spin ($a^*=L/M^2$)	Kerr (“astrophysical”)	Kerr-Newman
• Charge (Q)	Reissner-Nordström	

NASA/ESA and G. Bacon (STScI)

Black Hole Evaporation



Black hole

Quantum fluctuations

Throughout space-time, virtual particle-antiparticle pairs spontaneously arise and then annihilate each other.

Hawking radiation

If a pair arises close to the horizon of a black hole, one particle falls in, leaving the other to escape as "Hawking radiation."

Black hole evaporation

The black hole gradually evaporates as Hawking radiation carries away its energy.

Image: Lucy Reading-Ikkanda for Quanta Magazine

PBH Evaporation

- Black Holes evaporate through continuous emission of degrees of freedom, losing mass and angular momentum.
  - Lifetime ~ time required to evaporate
- (Low) Mass range: 10^{-5} g - 10^{-1} g - 10^{9} g
  - Mass range defined by CMB and BBN
  - Can also be much heavier, still around/evaporating today (other talks in this session)
- All kinematically-accessible particles are emitted (everything lighter than BH temp).
- Rest of talk: Focus on low mass PBH scenario (evaporation prior to BBN)
  1. dark matter emission from PBH evaporation
  2. dark radiation (massless graviton) emission from PBH evaporation
- These PBHs are not the DM, but their existence has important consequences for DM in a variety of mass ranges.

Dark Matter Emission from PBH Evaporation

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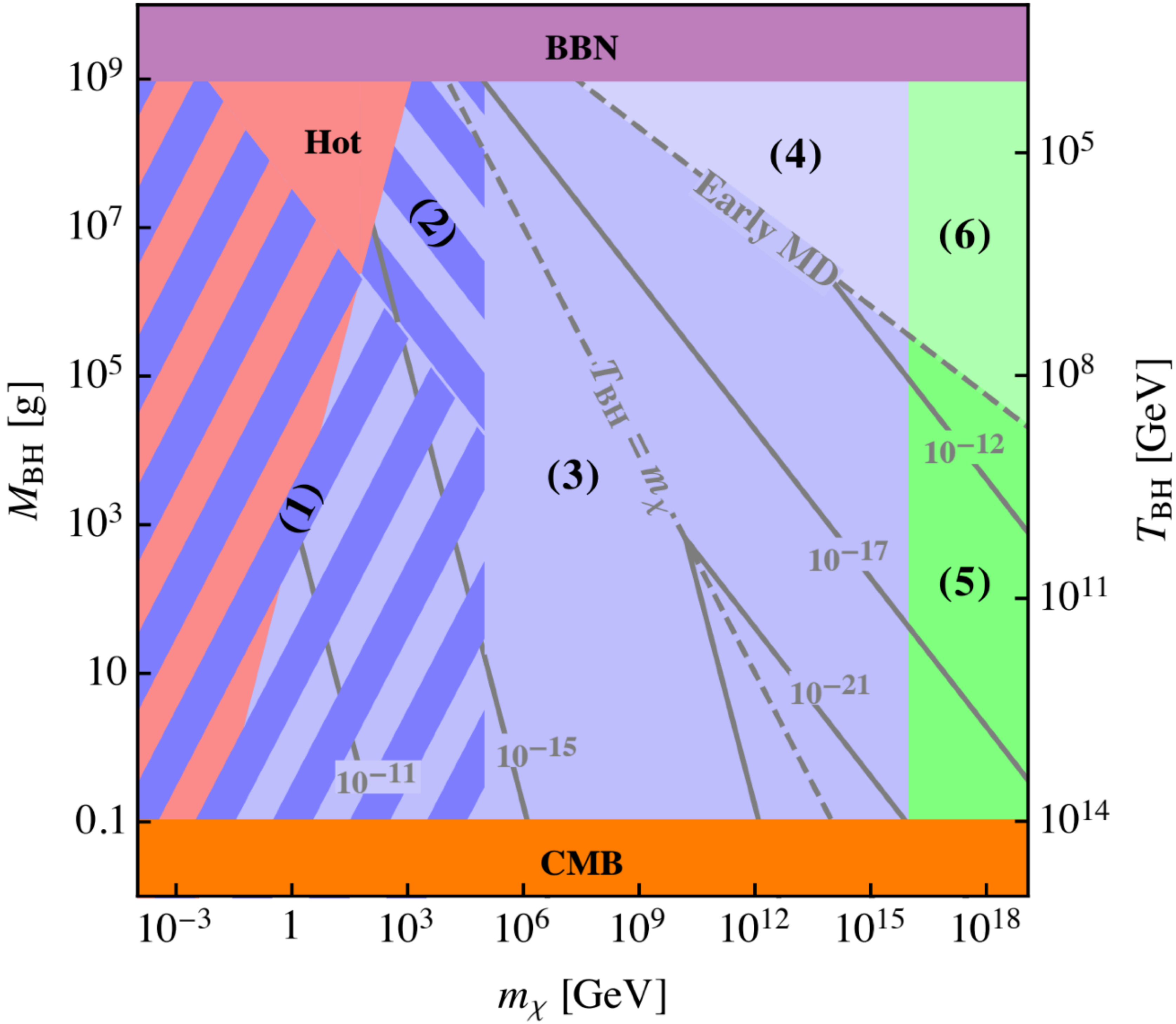
PBH Evaporation and Dark Matter

- If PBHs evaporate after the abundance of DM is set by another mechanism, PBH evaporation will provide a second inevitable contribution to the DM abundance.

	PBH evap. *before* DM production	**PBH evap. *after* DM production**
• **Freeze-out production** • WIMPs: 2-2 annihilation • SIMPs: 3-2 self-annihilation • Stronger interactions lead to less DM	no effect on DM abundance	extra source of DM
• **Freeze-in production** • e.g. FIMPs: produced via decay, scattering, or pair production • Weaker interactions lead to less DM	extra source of DM	extra source of DM
• **Gravitational production** • e.g. WIMPzilla: particle creation by the expansion of the universe acting on quantum fluctuations of the vacuum (also many other mechanisms)	extra source of DM	extra source of DM

Results



Sources of Dark Matter:

(1): freeze−out only

(2): freeze−out and/or PBH

(3): freeze−in and/or PBH

(4): freeze−in required plus PBH

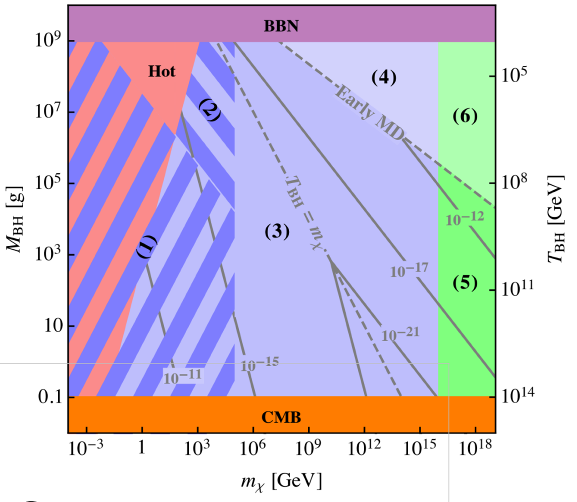
(5): WIMPZILLA and/or PBH

(6): WIMPZILLA required plus PBH

Note: effect depends on energy density in PBHs:

$$\beta(M) \equiv \frac{M\, n_{\rm PBH}(t_i)}{\rho(t_i)}$$

PBH evaporation and DM models



Summary

	PBH evap. *before* DM production	**PBH evap. *after* DM production**	**DM Properties?**
Freeze-out	no effect on DM abundance	extra source of DM	If there is an extra DM source, larger annihilation cross sections are consistent (improved detection prospects).
Freeze-in or Gravitational Production, **no EMDE**	extra source of DM	extra source of DM	Less DM needed from other production mechanism (even feebler couplings are viable).
Freeze-in or Gravitational Production, **EMDE**	extra source of DM	extra source of DM	Amount of DM produced by PBHs is independent of PBH abundance. Definitely need second production mechanism (PBHs can't do it alone).

Important to understand **interplay** of PBHs and other sources/production mechanisms for dark matter

Dark Radiation Emission from PBH Evaporation

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Dark Radiation from PBH Evaporation

- Everything that can be emitted will be emitted! Gravitons are especially interesting because spinning black holes have enhanced emission of particles with higher spin.

- Are PBHs spinning as they evaporate? Maybe a lot!

    - EMDE: tidal forces and density fluctuations can make collapsing regions non-spherical, which can lead to very large PBH spins

    - Accretion and mergers

- Observable effect: Massless gravitons (dark radiation) emitted from PBH evaporation could impact the effective number of relativistic degrees of freedom: $\Delta N_{\mathrm{eff}} = N_{\mathrm{eff}} - 3.046$

Dark Radiation from PBH Evaporation

- Assuming PBHs are abundant enough to initiate an EMDE and reheat the universe via their Hawking evaporation,

$$\Delta N_{\rm eff} = \frac{\rho_{\rm DR}(t_{\rm EQ})}{\rho_{\rm R}(t_{\rm EQ})}\left[N_\nu + \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\right]$$

- The ratio of energy densities at matter-radiation equality can be determined from the ratio at reheating time, scaled by g_* and $g_{*,S}$ at the appropriate temperatures,

$$\frac{\rho_{\rm DR}(t_{\rm EQ})}{\rho_{\rm R}(t_{\rm EQ})} = \frac{\rho_{\rm DR}(t_{\rm RH})}{\rho_{\rm R}(t_{\rm RH})}\left(\frac{g_*(T_{\rm RH})}{g_*(T_{\rm EQ})}\right)\left(\frac{g_{*,S}(T_{\rm EQ})}{g_{*,S}(T_{\rm RH})}\right)^{4/3}$$

- We use the `BlackHawk` public code to calculate the evolution of a distribution of PBHs and the associated time-dependent spectra of emitted DM particles and gravitons.

$$\rho_{\rm DR/SM}(t_{\rm RH}) = \int_0^1 da^*\,\frac{dn}{da^*}\int_0^{t_{\rm RH}} dt\int_0^{+\infty} dE\,E\,\frac{d^2N_{\rm DR/SM}}{dtdE}(M,a^*)$$

PBH spin

emission rates for
individual species

Precision Elements

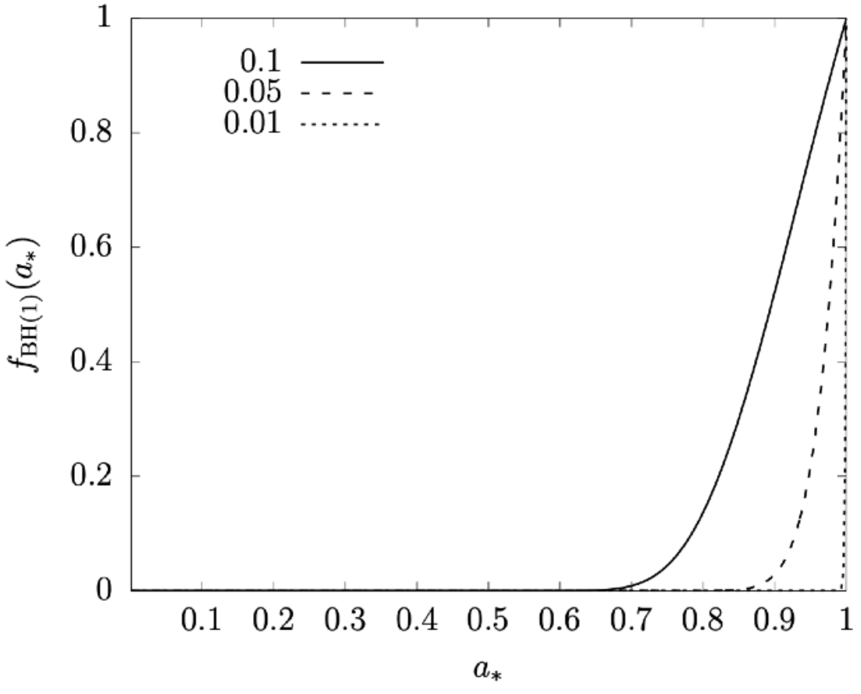
- **Precision calculation:**
  1. Extended PBH spin distributions
     - EMDE and mergers (next slide)
  2. Careful description of reheating time
     - t_{RH} = time at which last PBH (with lowest spin) evaporates
     - t_{RH} = average PBH lifetime, weighted by the spin distribution

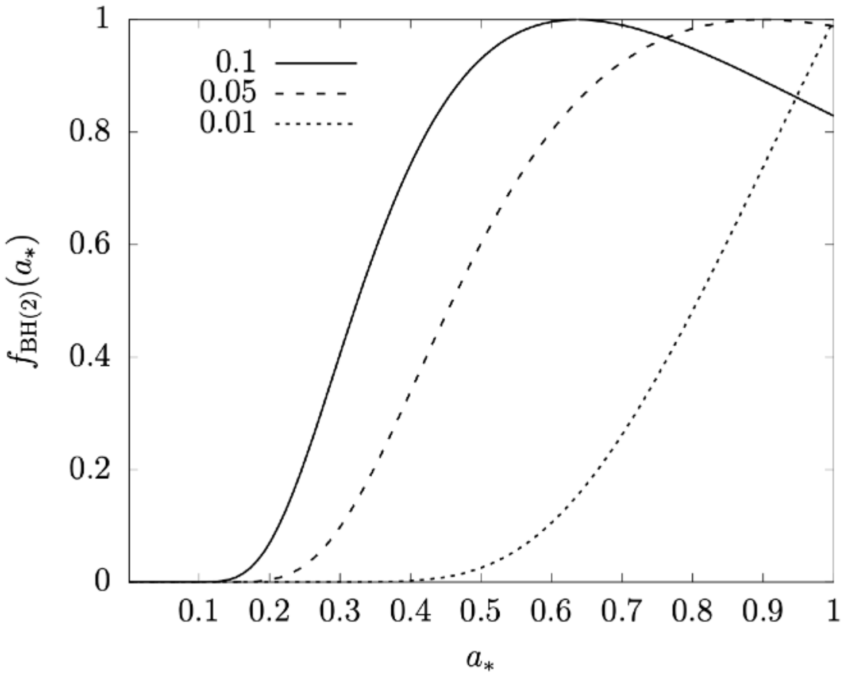
$$\langle\tau\rangle \equiv \int_0^1 \tau(M, a^*) \frac{dn}{da^*}\, da^*$$

  3. Precise expressions for the number of accessible degrees of freedom as a function of temperature.
     - $g_*(T)$ and $g_{*,S}(T)$ from `SuperIso Relic`
- Compare with current limits and future sensitivities
  - CMB1,2 (Planck), BBN (w/`AlterBBN`), and CMB Stage 4

Benchmark Spin Distributions

- EMDE Harada et al. (2017)
  - 1st order effect from deviation of the boundary of a volume from spherical
  - 2nd order effect from density fluctuations inside the volume

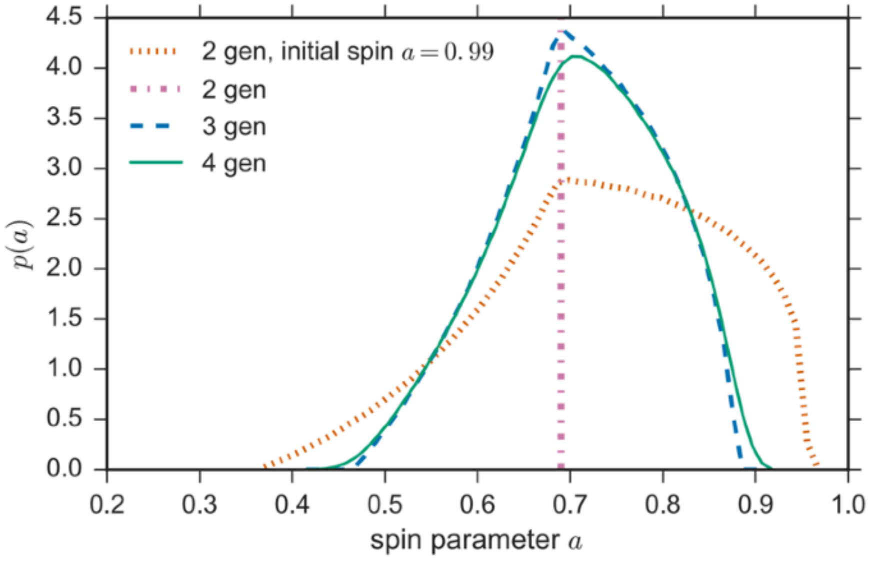




- In both cases, spin distribution depends on the mean variance of the density perturbations at horizon entry

$$\sigma_{\mathrm{H}} = \langle \delta_s(t_{\mathrm{H}})^2 \rangle^{1/2}$$

- Mergers Fishbach et al. (2017)
  - Assume an initial population of PBHs that inspiral and merge

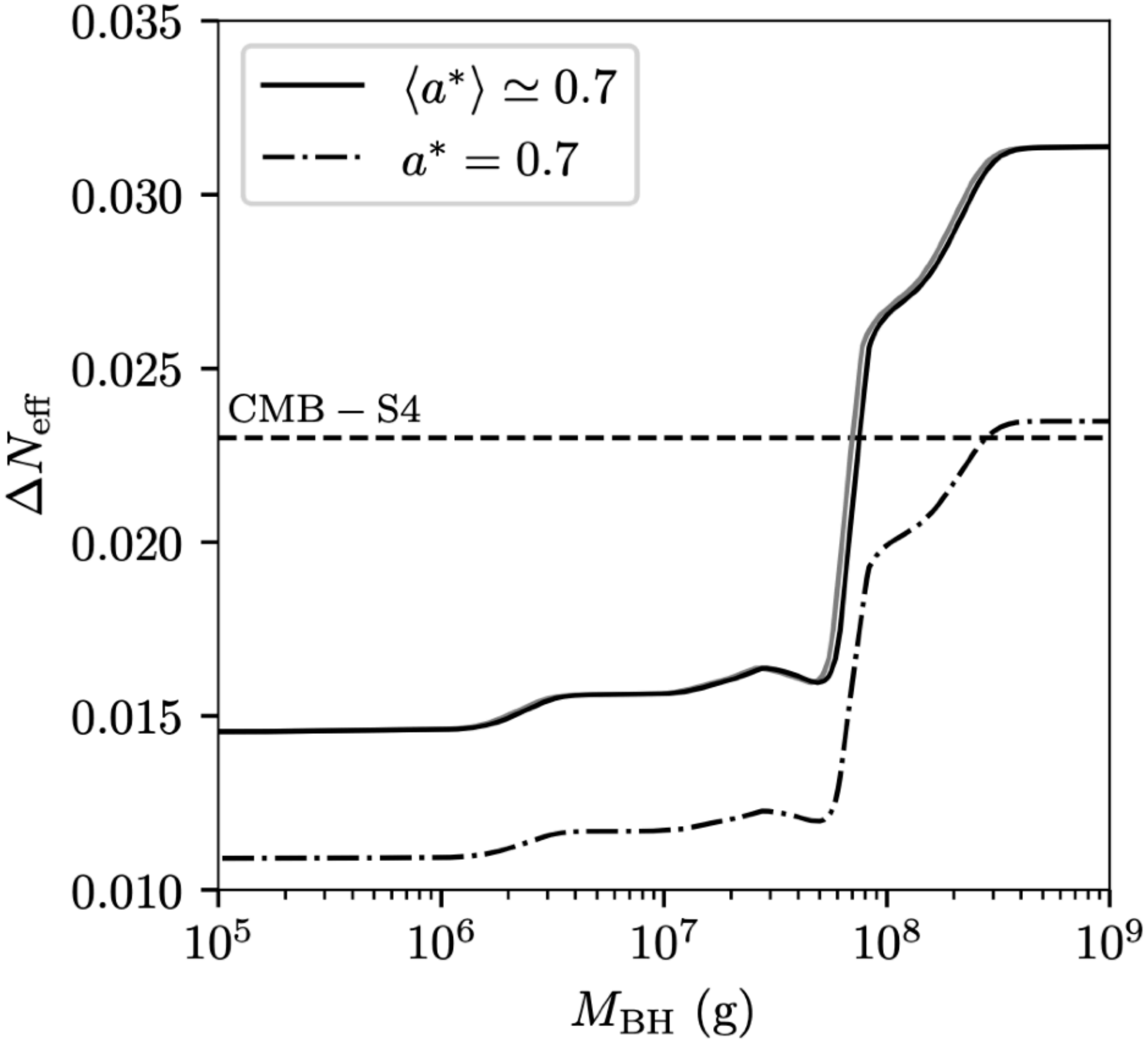


  - Irrespective of initial spins, always converge to a distribution peaked at

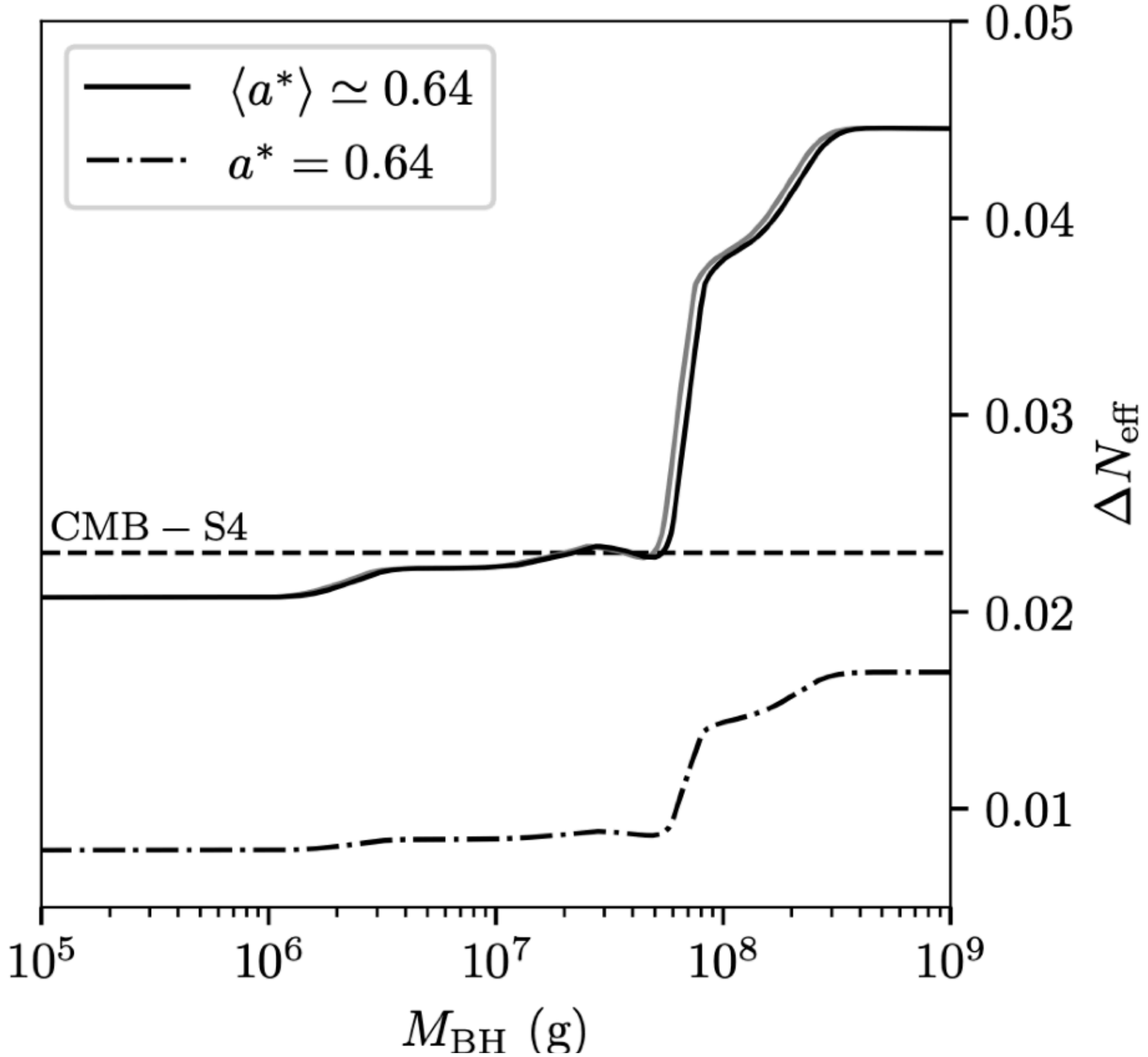
$$a^* \simeq 0.7$$

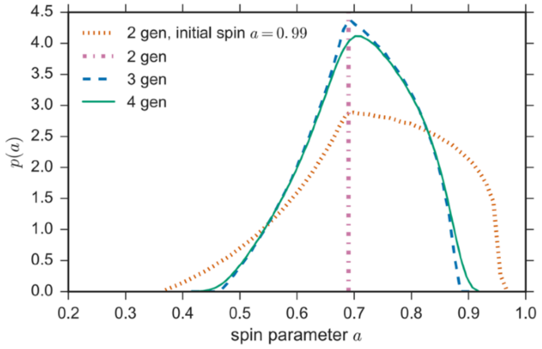
Monochromatic vs. Extended Spin Distributions

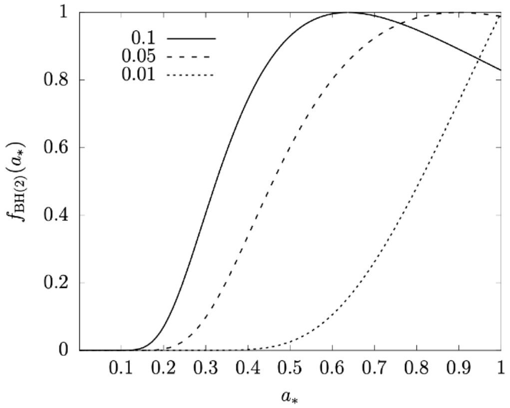
Mergers



EMDE (2nd Order)

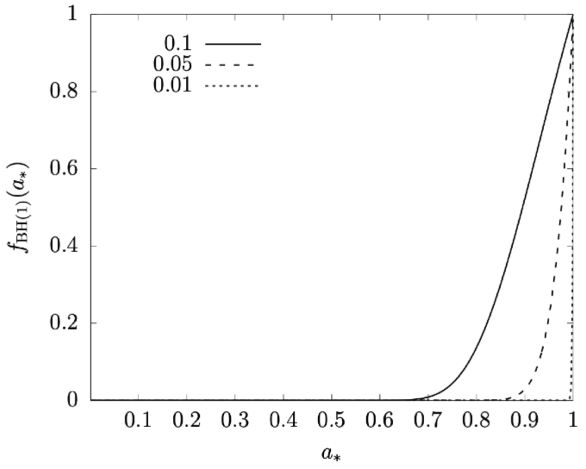


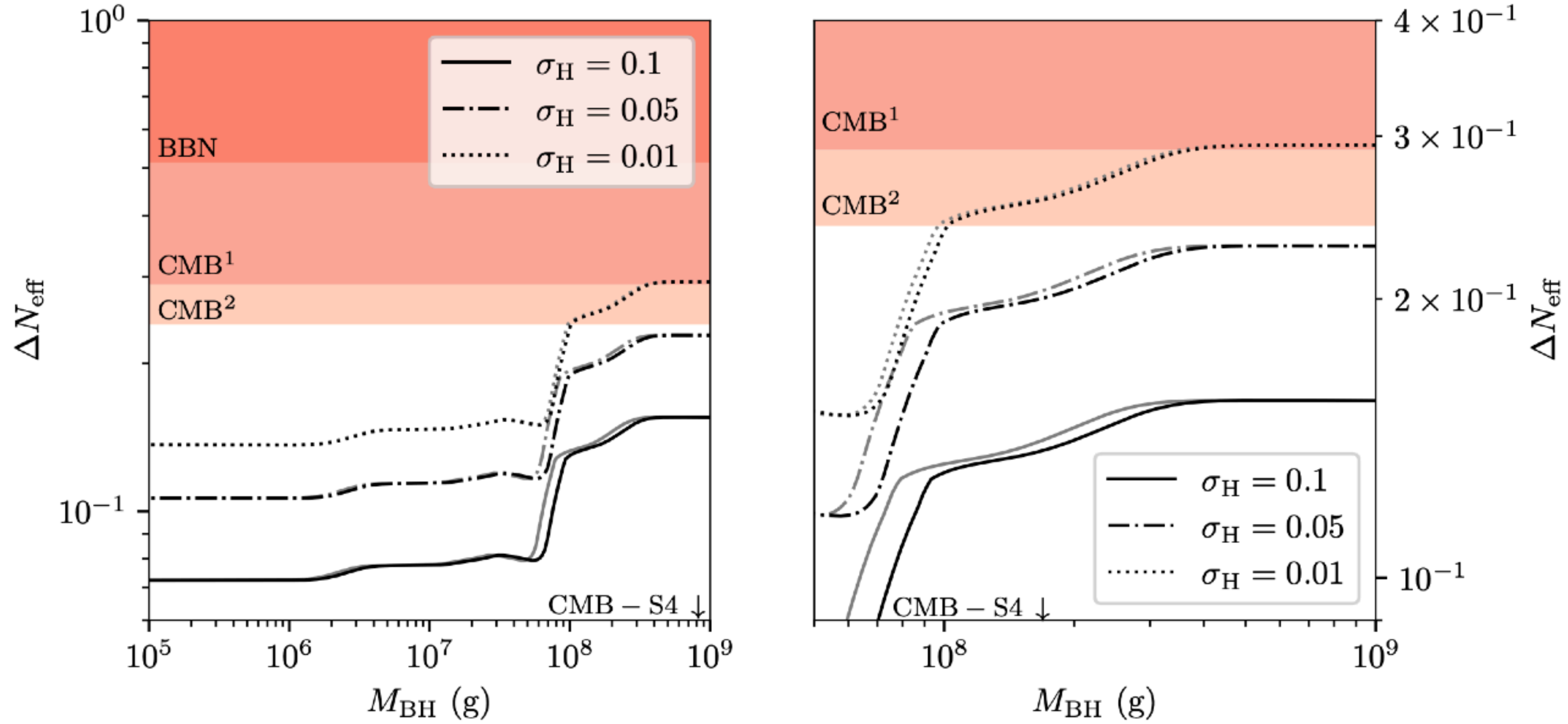




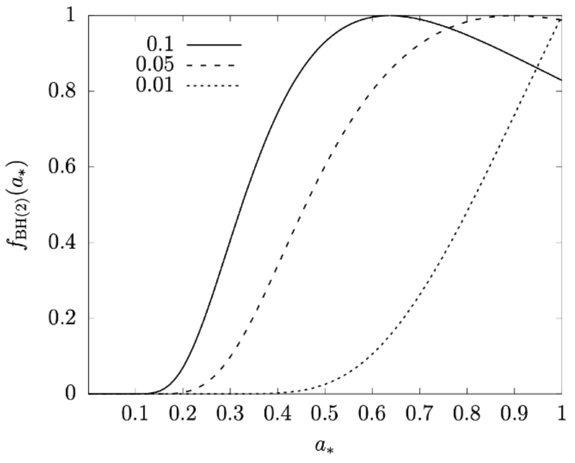
Formation during EMDE

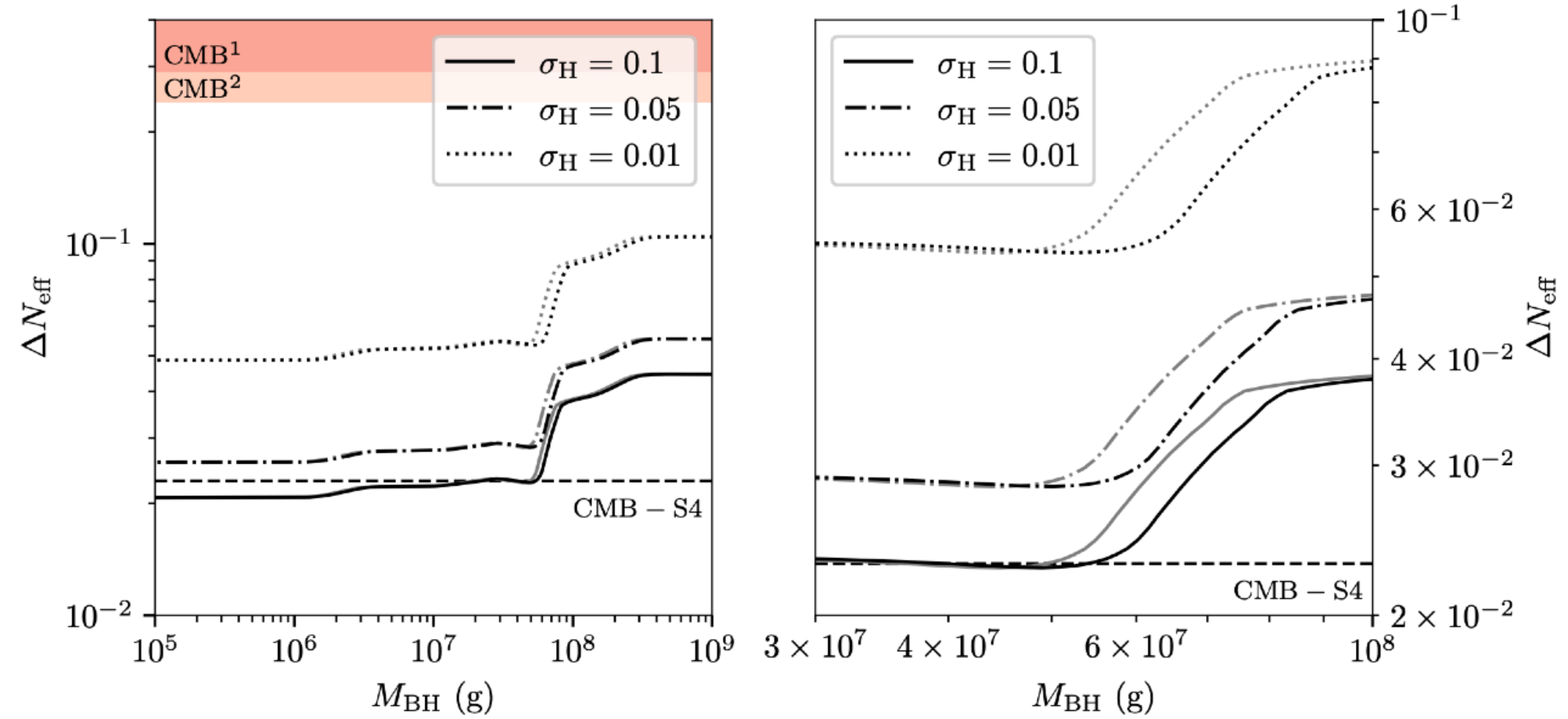
- 1st Order





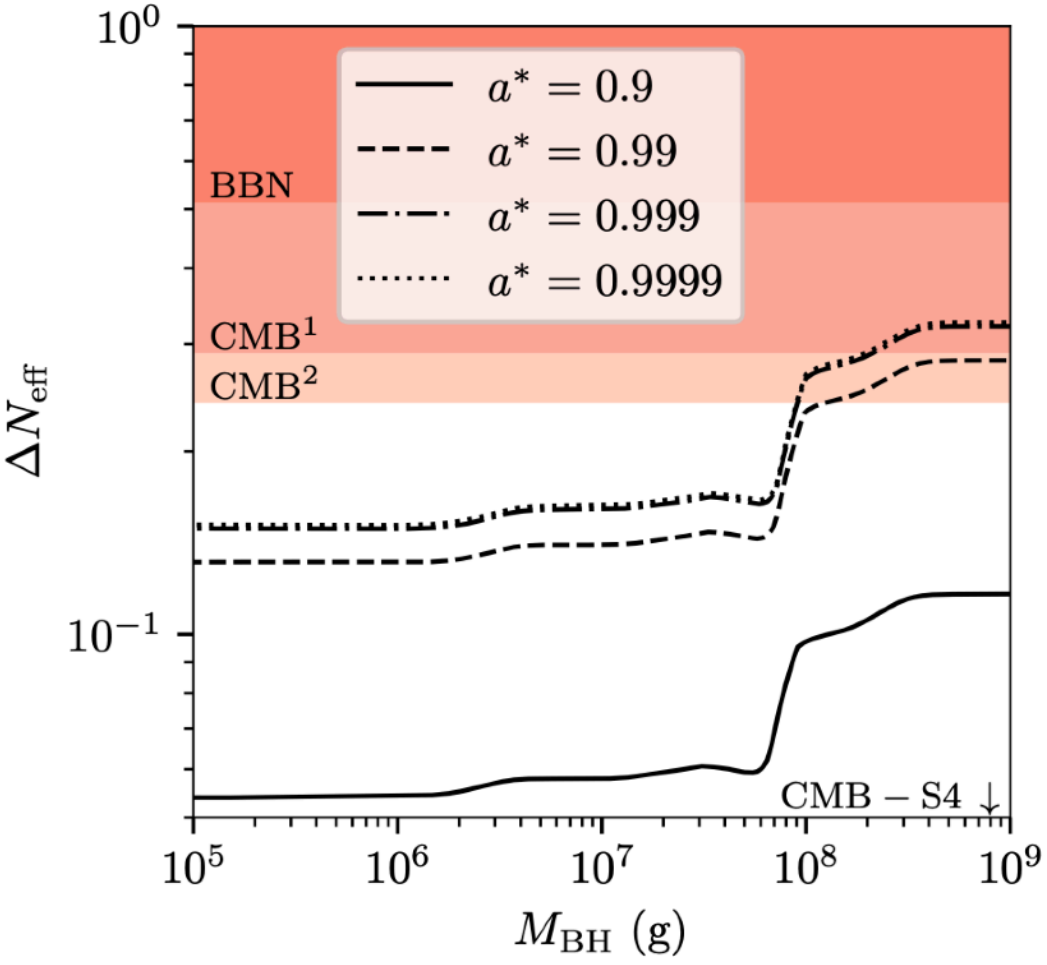
- 2nd Order

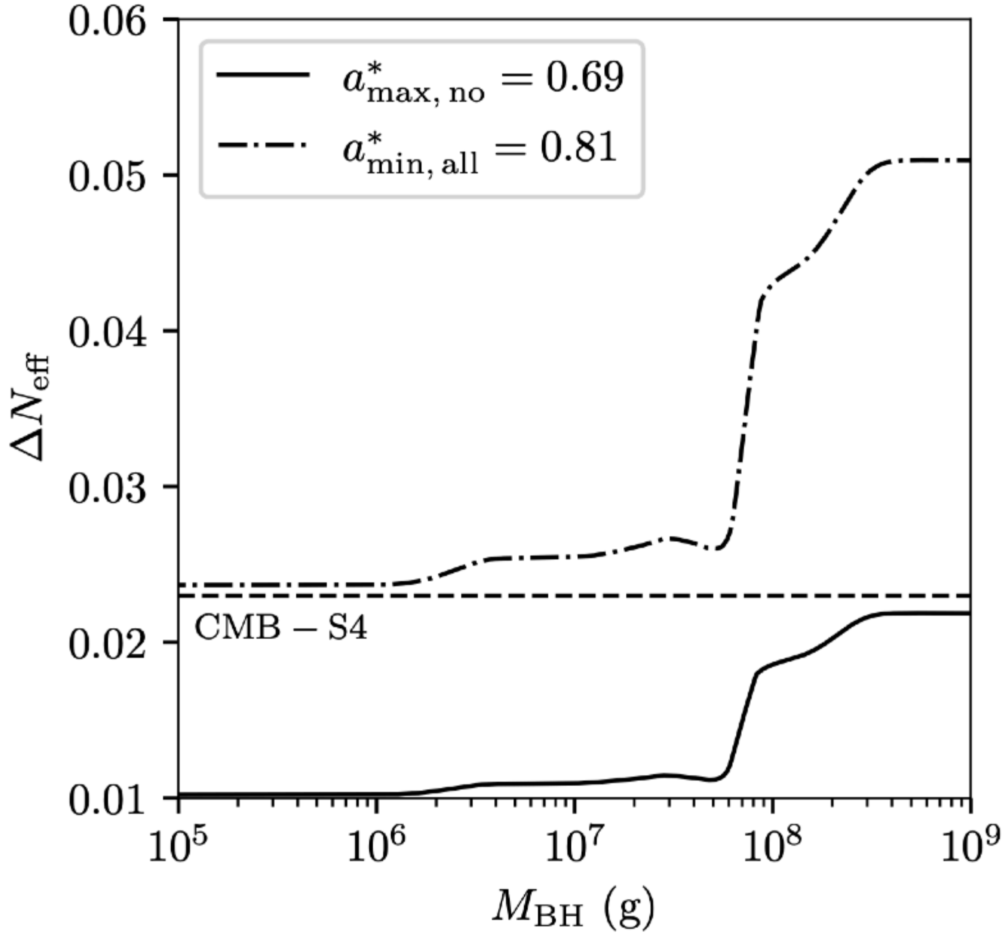




Near-Extremal PBH Spins

- Monochromatic spin distributions
- Larger PBH spins → more graviton emission → larger contribution to $\Delta N_{\rm eff}$
- Enhancement in $\Delta N_{\rm eff}$ saturates as a* → 1.
- Largest PBH masses already excluded
- CMB-S4 will probe all monochromatic spin distributions with $a^*_{\rm min,\,all} = 0.81$





Dark Radiation from PBH Evaporation

Summary

- First precision study of dark radiation from evaporation of Kerr PBHs
- Precision elements: extended PBH spin distributions, careful treatment of reheating time, and precise description of accessible degrees of freedom
- An extended spin distribution leads to 1) a distribution of evaporation times and 2) enhanced graviton emission from the highest spin components (so larger $\Delta N_{\rm eff}$).
- Primary application is precision results for PBHs that formed during an EMDE
- Assuming PBHs come to dominate the energy density of the universe prior to evaporation, CMB-S4 will be sensitive to nearly all EMDE scenarios and a generous range of monochromatic spins.

PBH Formation, Radiation, Evaporation

- PBHs with masses less than 10^9 g would have evaporated prior to BBN
- Hawking evaporation can be an important dark matter production mechanism, and interplay with typical production mechanisms (freeze-out, freeze-in, gravitational…) must be considered.
- Evaporation of spinning PBHs can result in substantial contributions to $\Delta N_{\rm eff}$. Given Planck and CMB-S4 sensitivities, precision calculations are now necessary.
- PBHs are fascinating targets for theoretical and phenomenological studies!