Dark Radiation from Spinning PBHs in the Early Universe - Precision Calculation and Constraints

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

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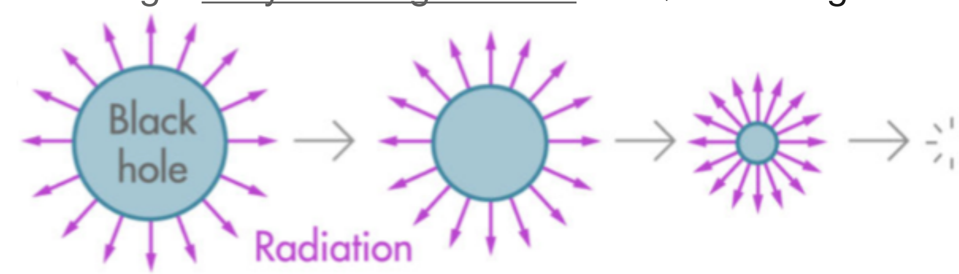
arXiv:2104.04051 (*Phys.Rev.D* 103 (2021) 12, 123549)

Dark Radiation from PBH Evaporation

- Black Holes evaporate through continuous emission of degrees of freedom, losing mass and angular momentum.
    - Lifetime = time required to evaporate

Image: Lucy Reading-Ikkanda for Quanta Magazine



- (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
- 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!
    - Early Matter Dominated Era: tidal forces and density fluctuations can make collapsing regions non-spherical, which can lead to very large PBH spins
    - Mergers, accretion
- Observable effect: Massless gravitons (dark radiation) emitted from PBH evaporation could impact the effective number of relativistic degrees of freedom: $\Delta N_{\rm eff} = N_{\rm eff} - 3.046$

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 SM 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

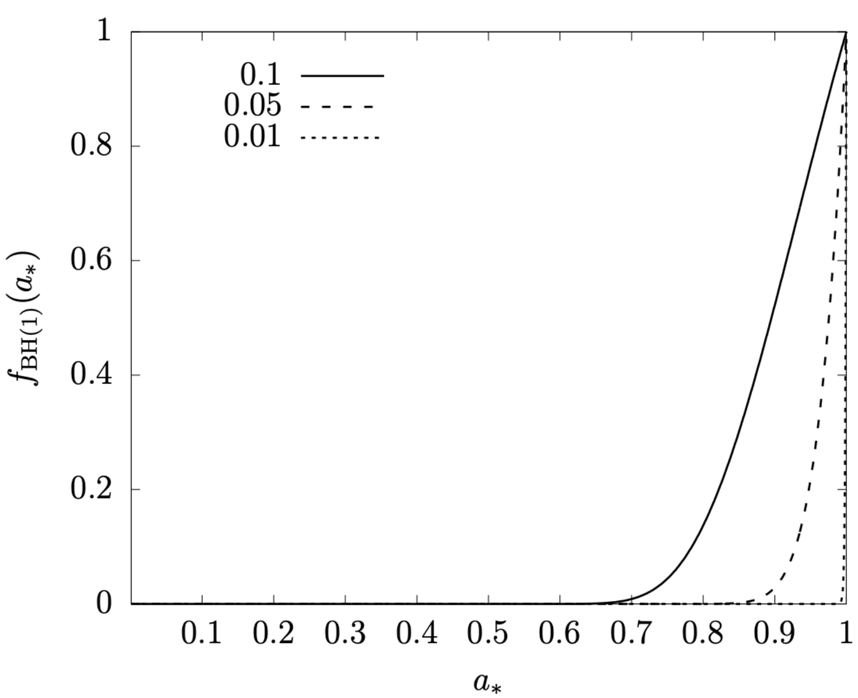
$$\langle \tau \rangle \equiv \int_0^1 \tau(M, a^*) \frac{dn}{da^*} \, da^*$$

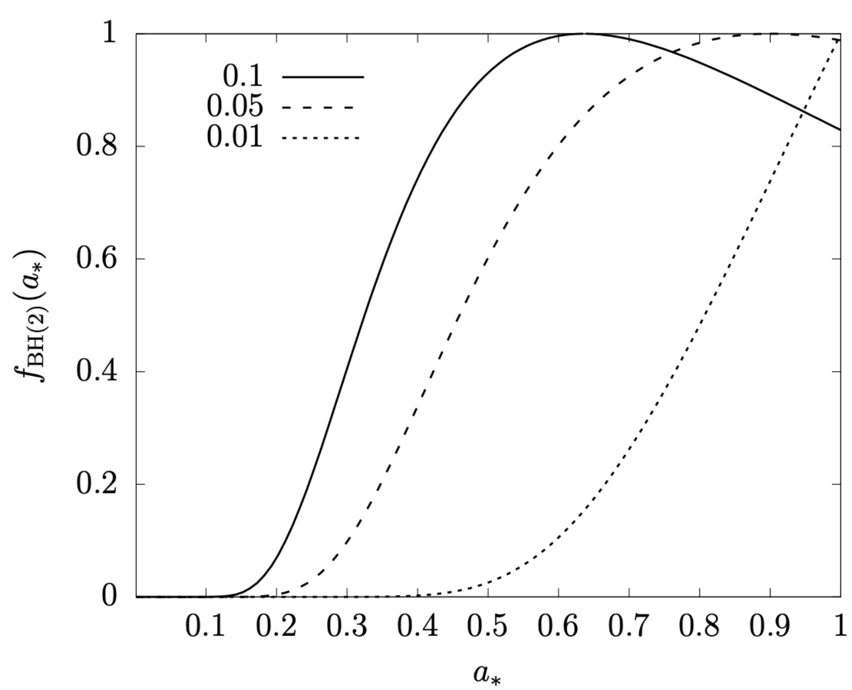
  3. Precise expressions for the number of accessible degrees of freedom as a function of temperature.
     - $g_*(T)$ and $g_{*,S}(T)$ from `SuperIso Relic`

- 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

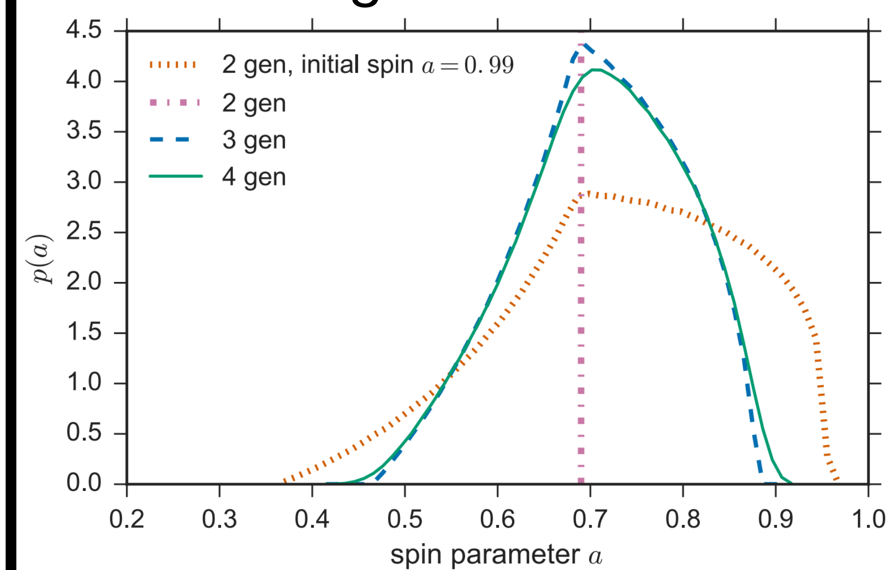




- In both cases, spin distribution depends on the mean variance of the density perturbations at horizon entry

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

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

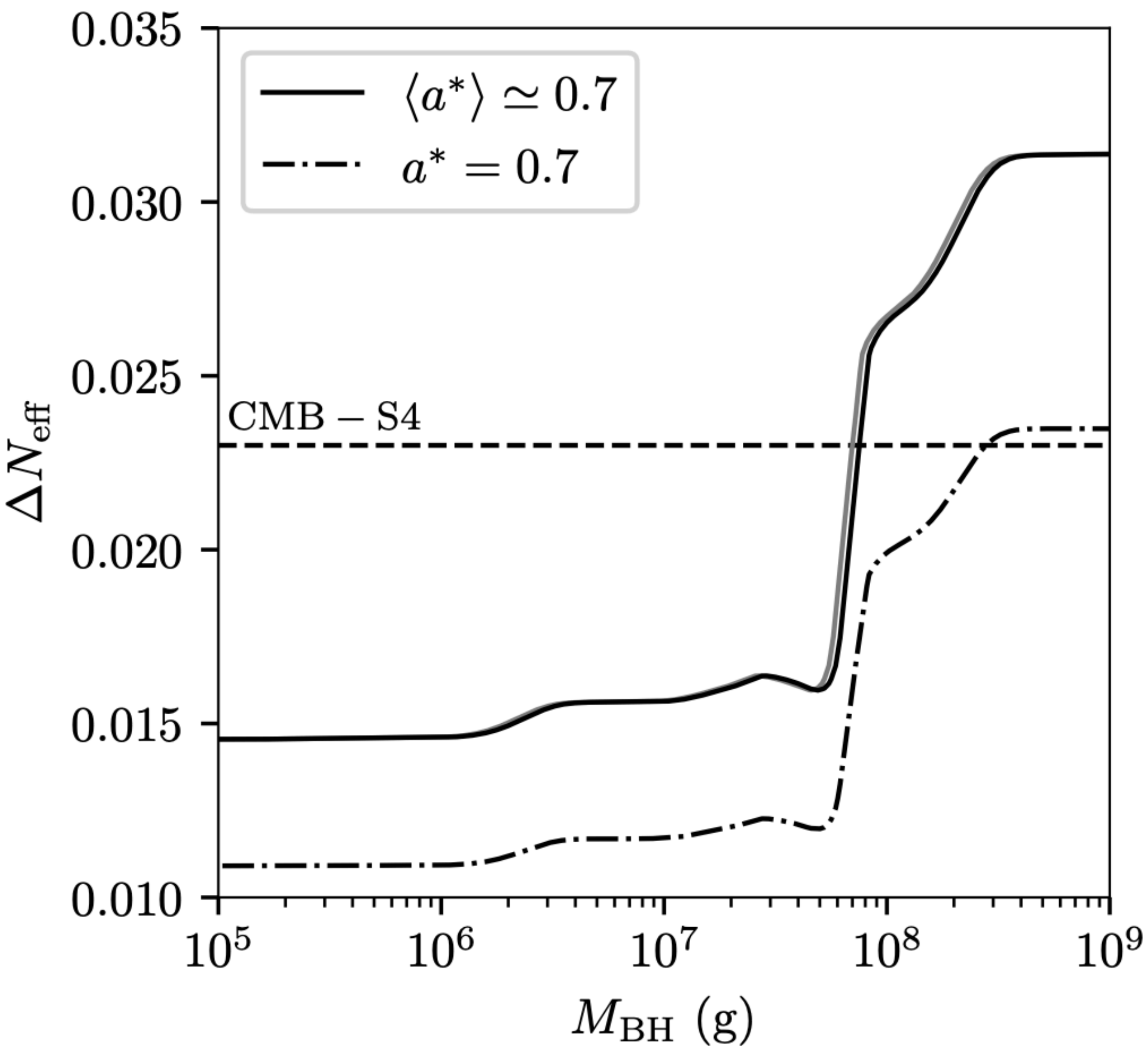


  - Irrespective of initial spins, always converge to a distribution peaked at

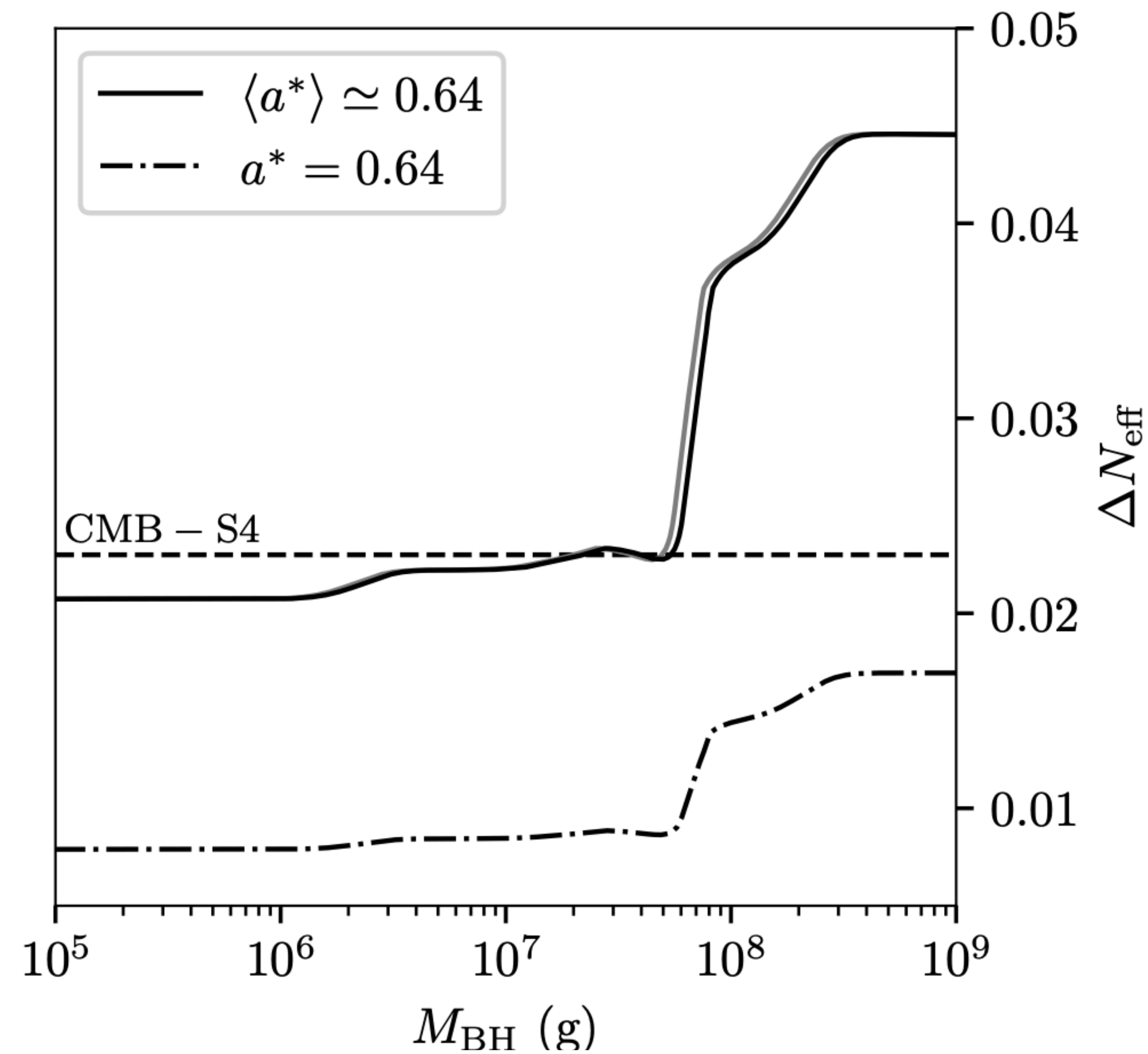
$$a^* \simeq 0.7$$

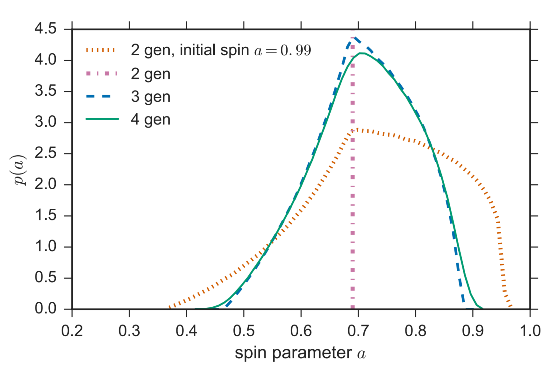
Monochromatic vs. Extended Spin Distributions

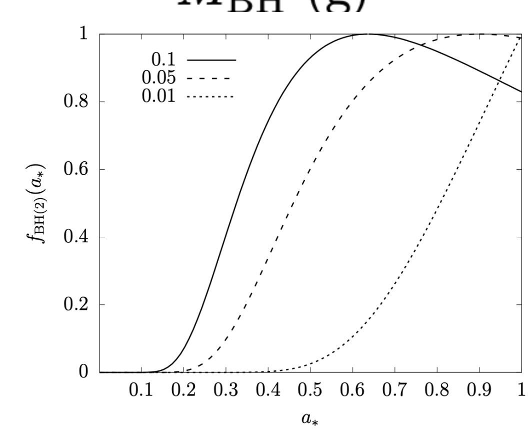
Mergers



EMDE (2nd Order)

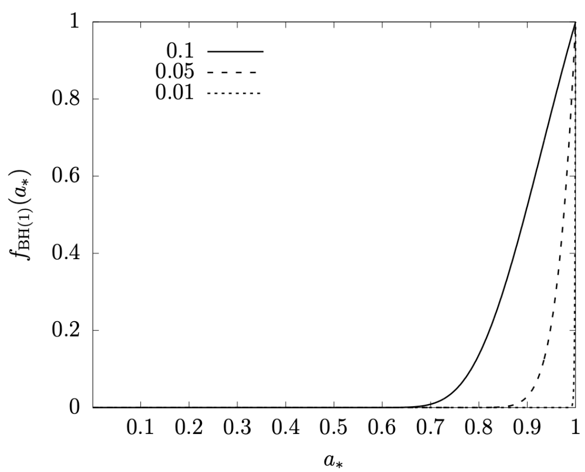


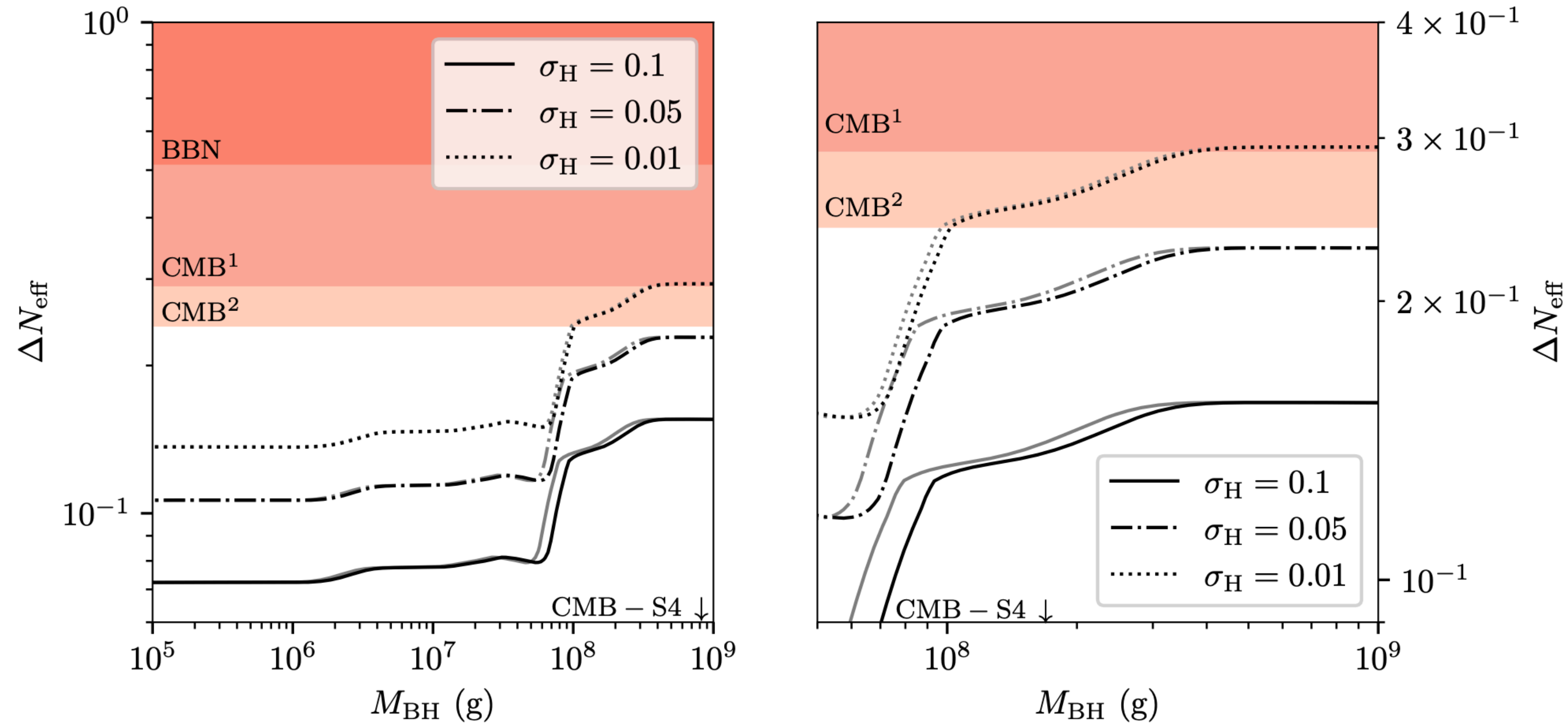




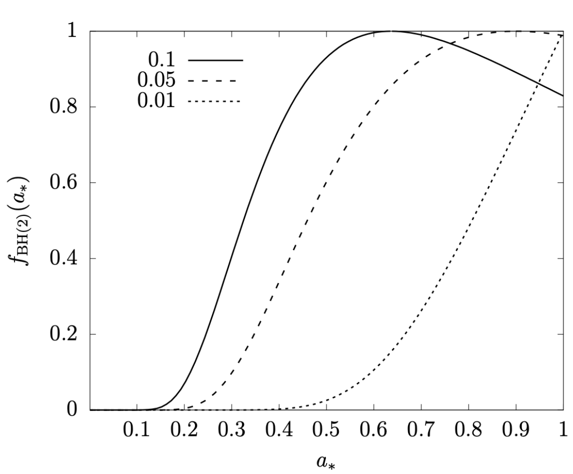
Formation during EMDE

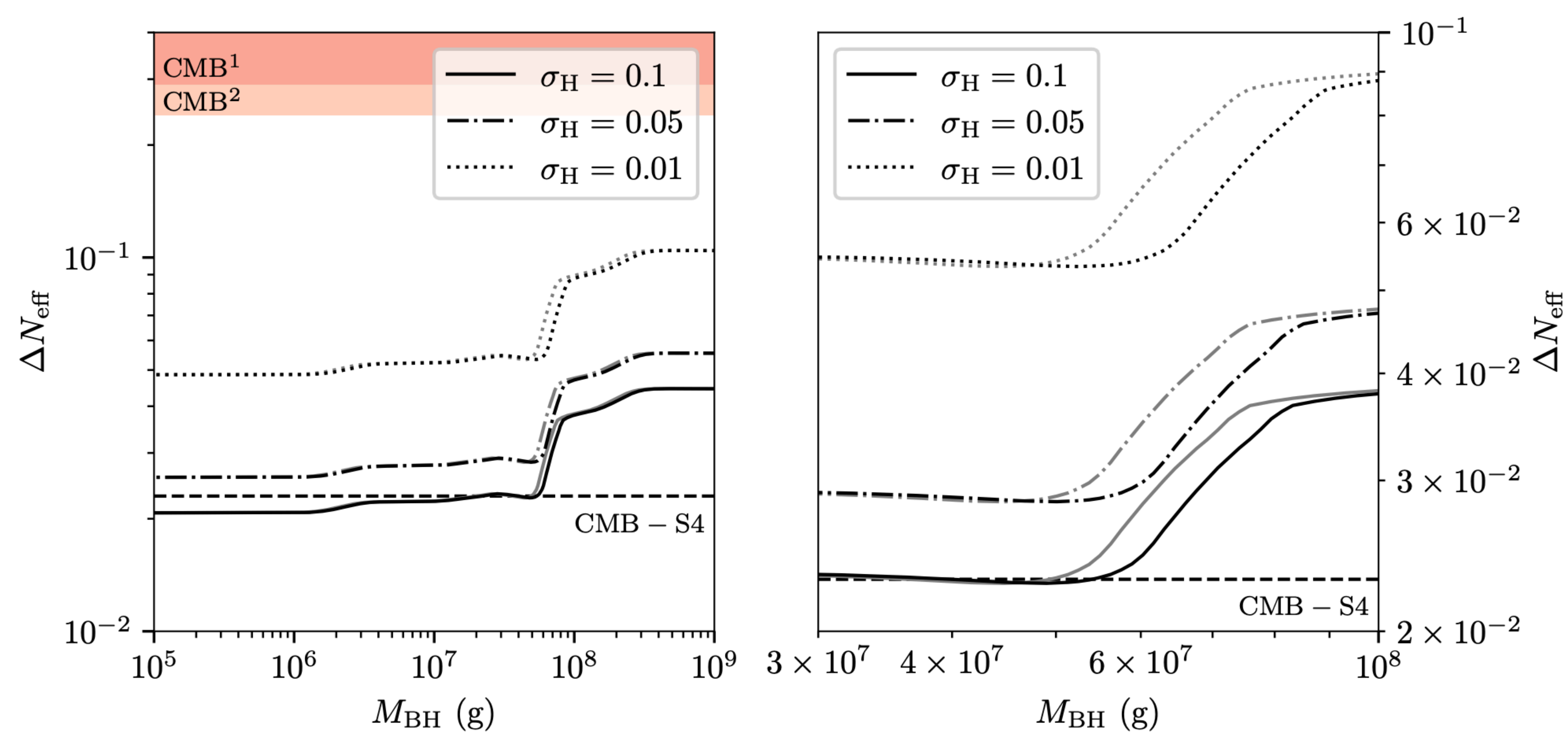
- 1st Order





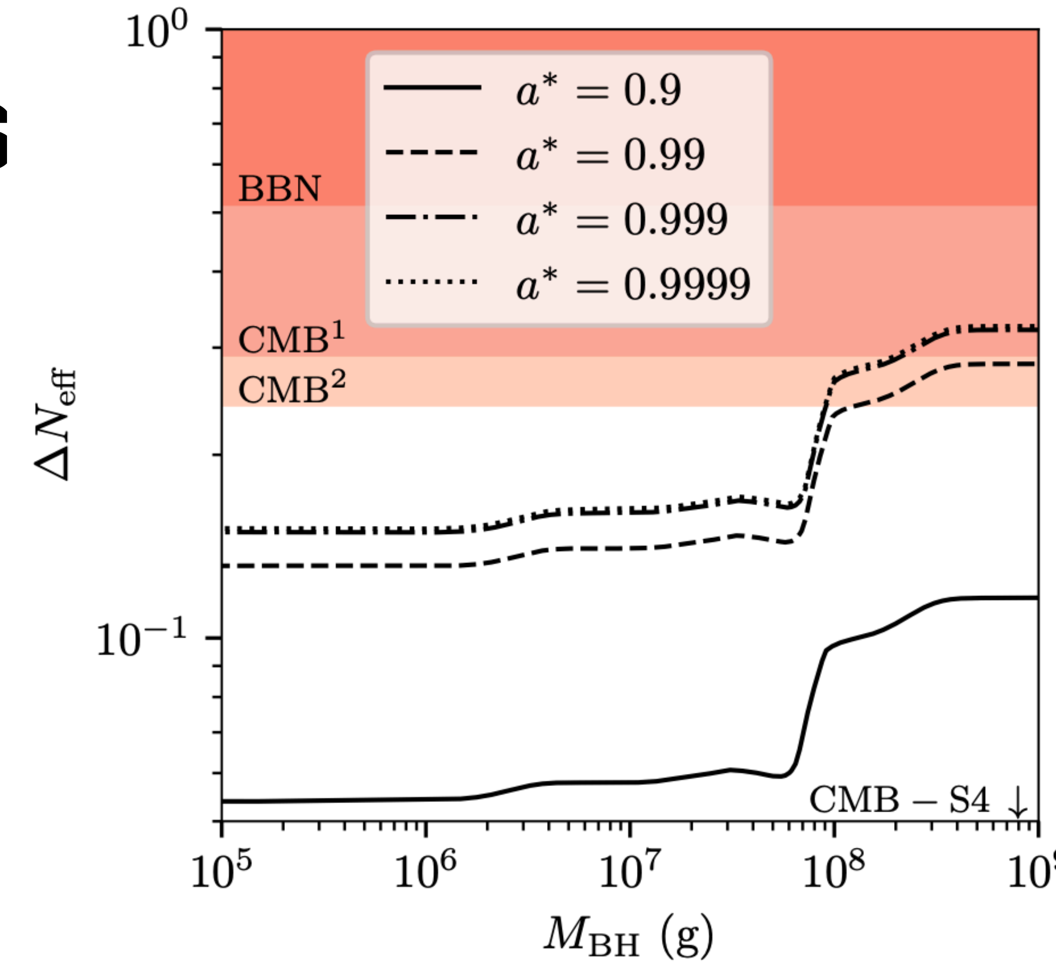
- 2nd Order

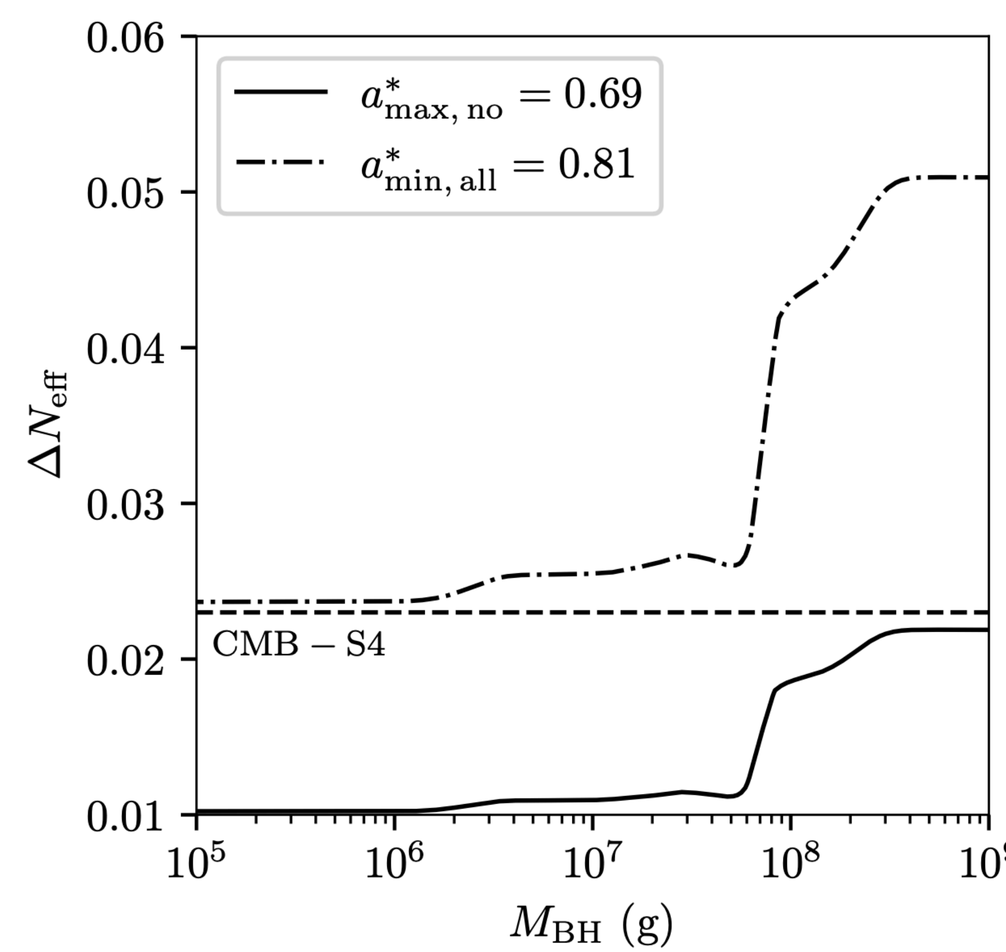




Near-Extremal PBH Spins

- 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

- Given Planck and CMB-S4 sensitivities, necessary to do precision calculations of dark radiation from evaporation of Kerr PBHs.

- First precision study: 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 $\Delta N_{\rm eff}$).

- Assumption is that PBHs are abundant enough to dominate the energy density of the universe prior to evaporation (strongest constraints). If PBHs do not dominate, constraints should be recalculated.

- If PBHs dominate the energy density of the universe prior to evaporation, **CMB-S4 will be sensitive to nearly all EMDE scenarios and all PBH masses <10^9g with monochromatic spins greater than a*=0.81**