Primordial Black Hole Domination
Dark Matter, Dark Radiation, and Gravitational Waves

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Fermilab KICP

+ Hooper, McDermott 1905.01301
+Hooper, March-Russell, McDermott, Petrossian-Byrne 2004.00618

Chung-Ang University Beyond Standard Model Workshop — Feb 2, 2021

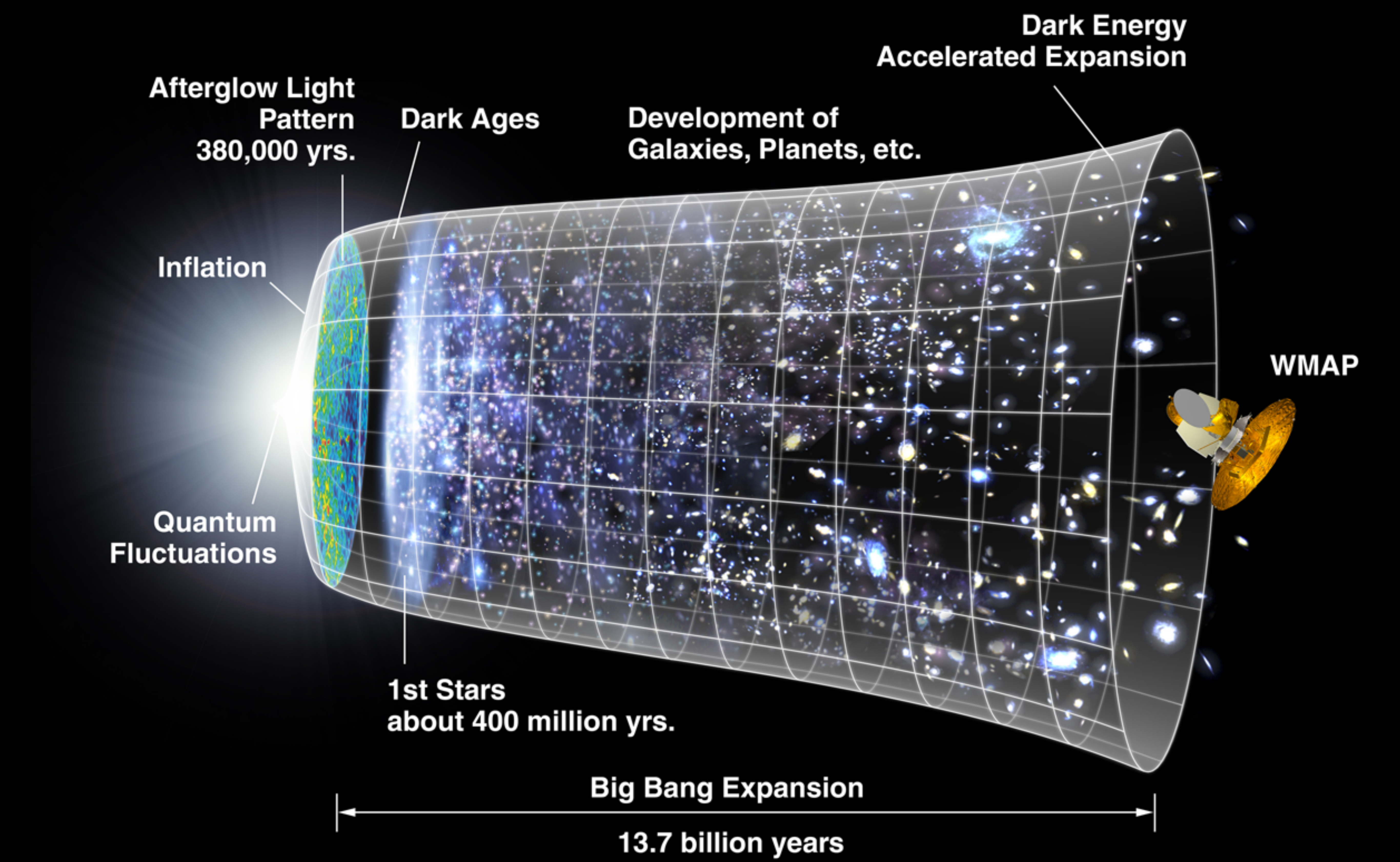

Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

Image: WMAP

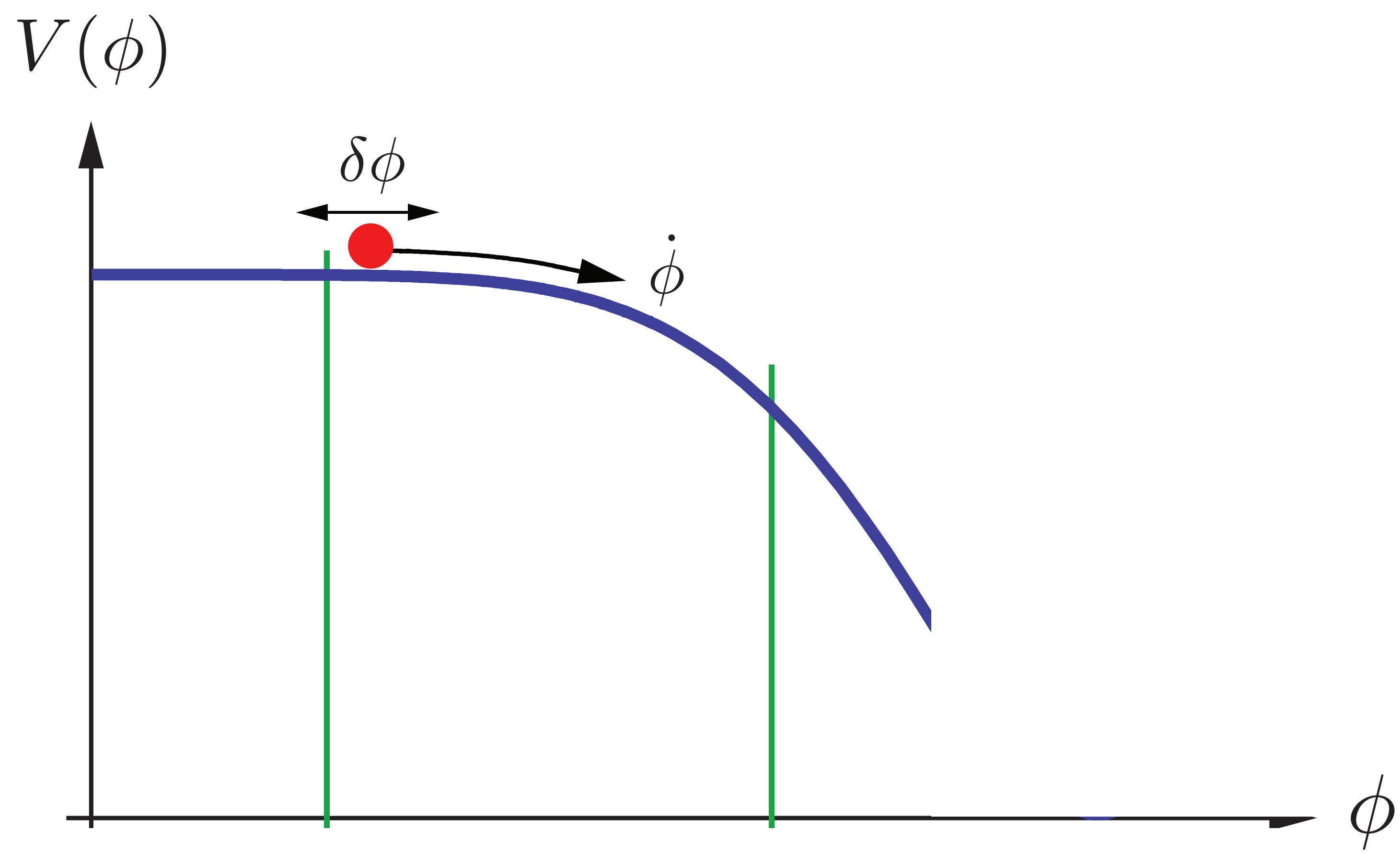
Canonical Cosmological Timeline

$t \sim 0$

Inflation

Exponential expansion driven by scalar field

Solves Horizon & Flatness problems



$t \sim \mathrm{sec}$

$t \sim 10^5\ \mathrm{yr}$

Generates perturbations via quantum fluctuations, seeds LSS

Not tested yet, but something like this almost certainly took place

$t \sim 13.7\ \mathrm{Gyr}$

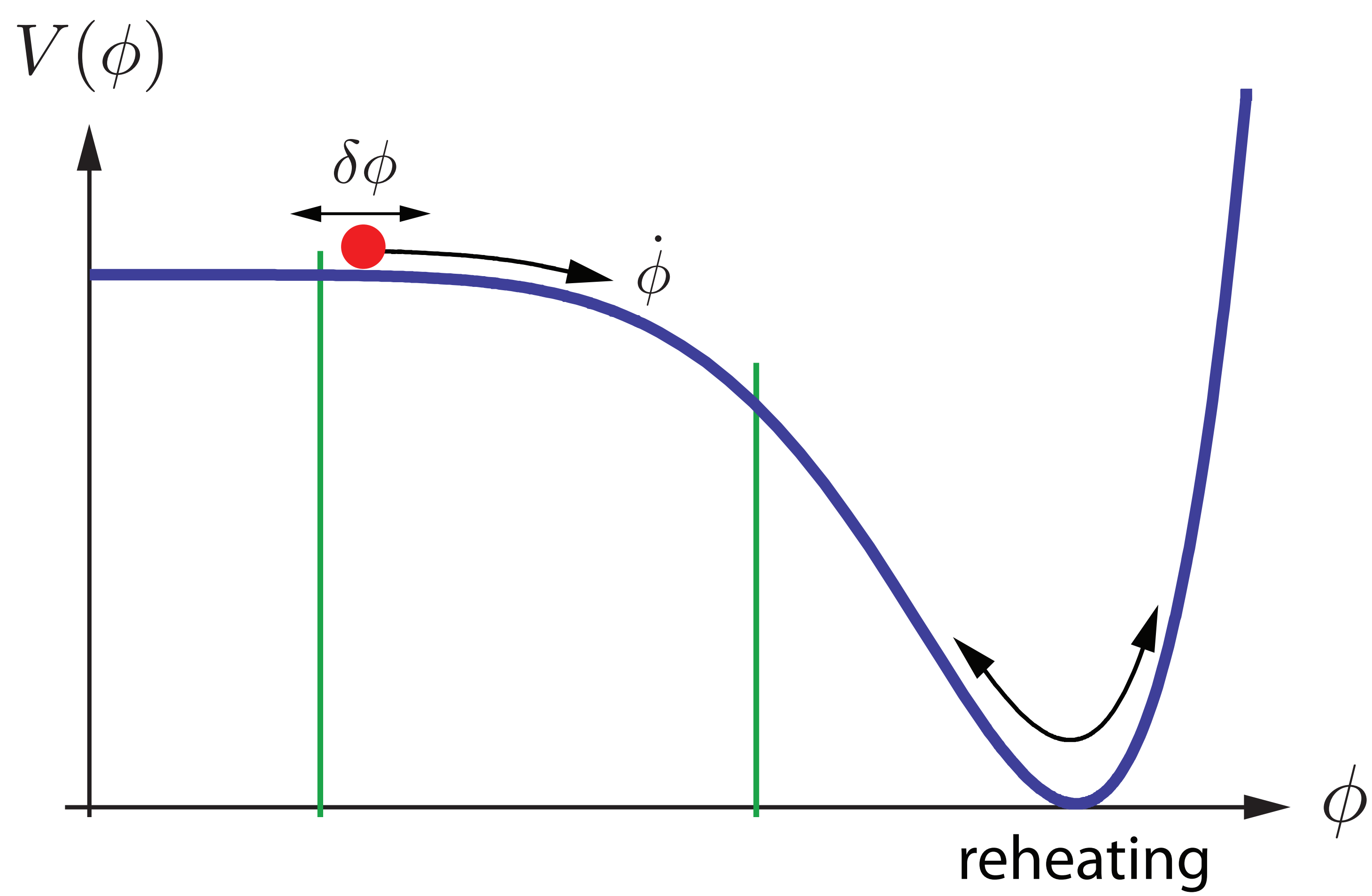
Canonical Cosmological Timeline

$t \sim 0$

Inflation

Reheating

$$\rho_{\text{inf}} \sim \rho_{\text{rad}} \propto T^4$$



$t \sim \text{sec}$

$t \sim 10^5\ \text{yr}$

Inflation* transfers potential energy to SM radiation

Eventual radiation domination required for BBN

$t \sim 13.7\ \text{Gyr}$

Canonical Cosmological Timeline

$t \sim 0$

Inflation

Reheating

Baryogenesis

Inflation exponentially dilutes pre-existing densities

Need dynamical mechanism to generate asymmetry

$t \sim \mathrm{sec}$

$t \sim 10^5\ \mathrm{yr}$

$t \sim 13.7\ \mathrm{Gyr}$

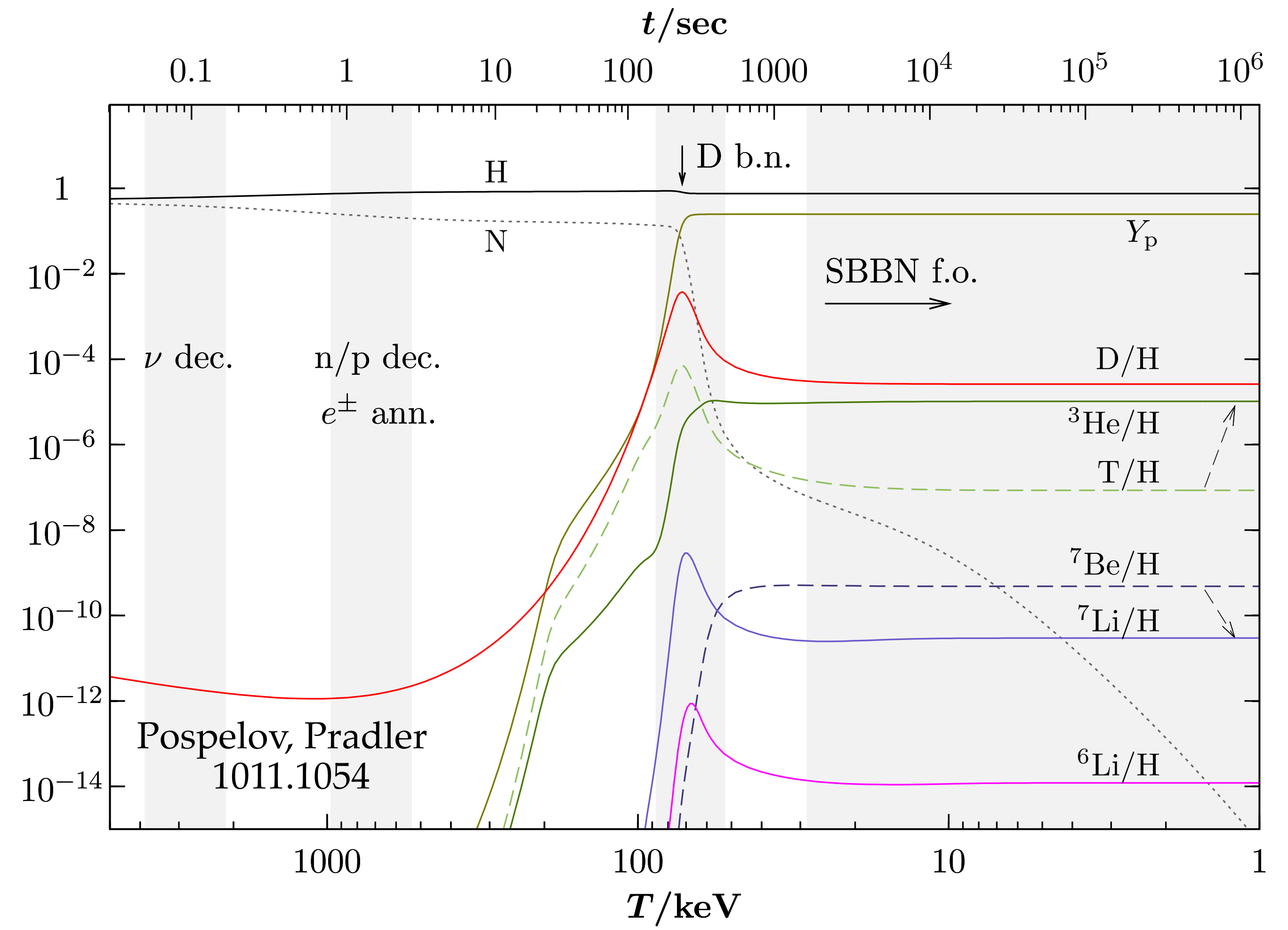
Canonical Cosmological Timeline

$t \sim 0$

Inflation

Reheating

Baryogenesis



$t \sim$ sec

BBN

Measured light element yields agree with observations

Inputs: SM nuclear rates, 3 flavors of decoupled neutrinos, and

$$\eta_b \equiv \frac{n_b}{s} \sim 10^{-10} \qquad n/p \sim 1/5$$

Requires baryon asymmetry and a radiation dominated universe T > few MeV

Canonical Cosmological Timeline

$t \sim 0$

Inflation

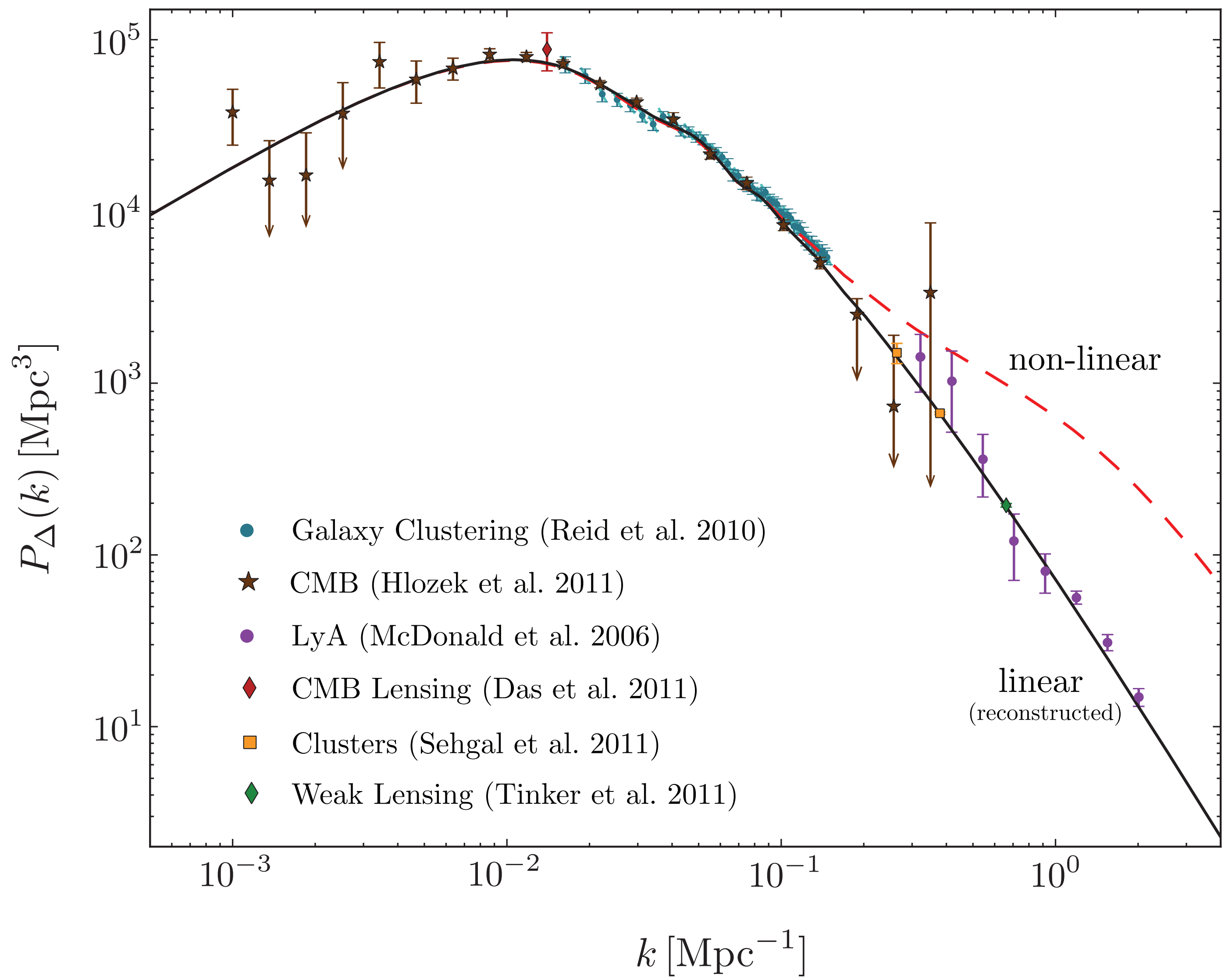
Reheating

Baryogenesis

$t \sim \text{sec}$ BBN

$t \sim 10^5$ yr **MR Equality**

$t \sim 13.7$ Gyr



Matter power spectrum in excellent agreement with data

Density perturbations grow linearly in matter dominated era

Integrated probe of late universe physics

Canonical Cosmological Timeline

$t \sim 0$

Inflation

Reheating

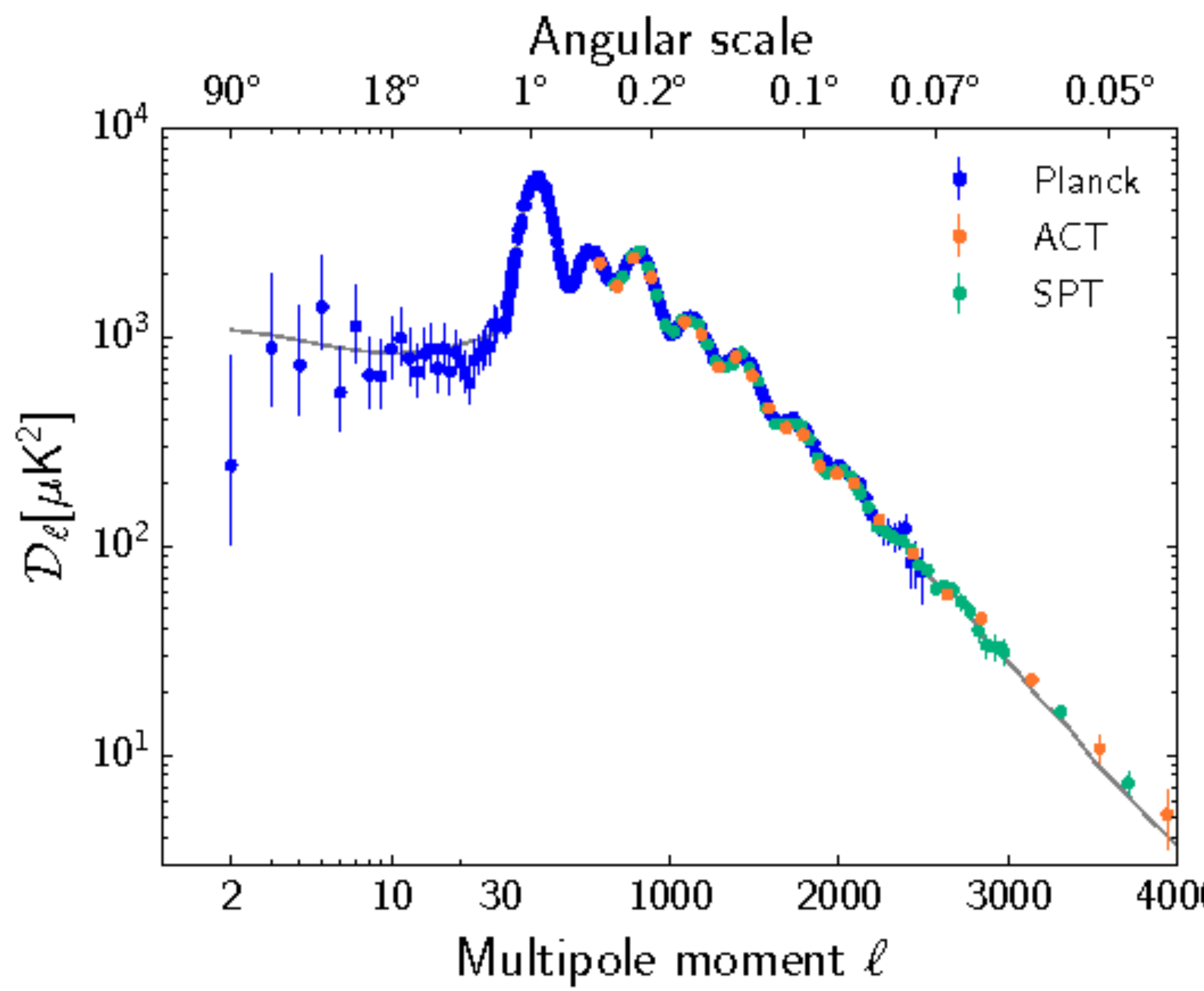
Baryogenesis

$t \sim \text{sec}$ BBN

$t \sim 10^5$ yr MR Equality

CMB

$t \sim 13.7$ Gyr



Measured CMB power spectra
Excellent agreement with data

Integrated probe of late universe physics

Canonical Cosmological Timeline

$t \sim 0$

Inflation

Reheating

Baryogenesis

Lots of model dependence

Can change order/details of events

EWSB or QCD PT (optional)

$t \sim \mathrm{sec}$ BBN

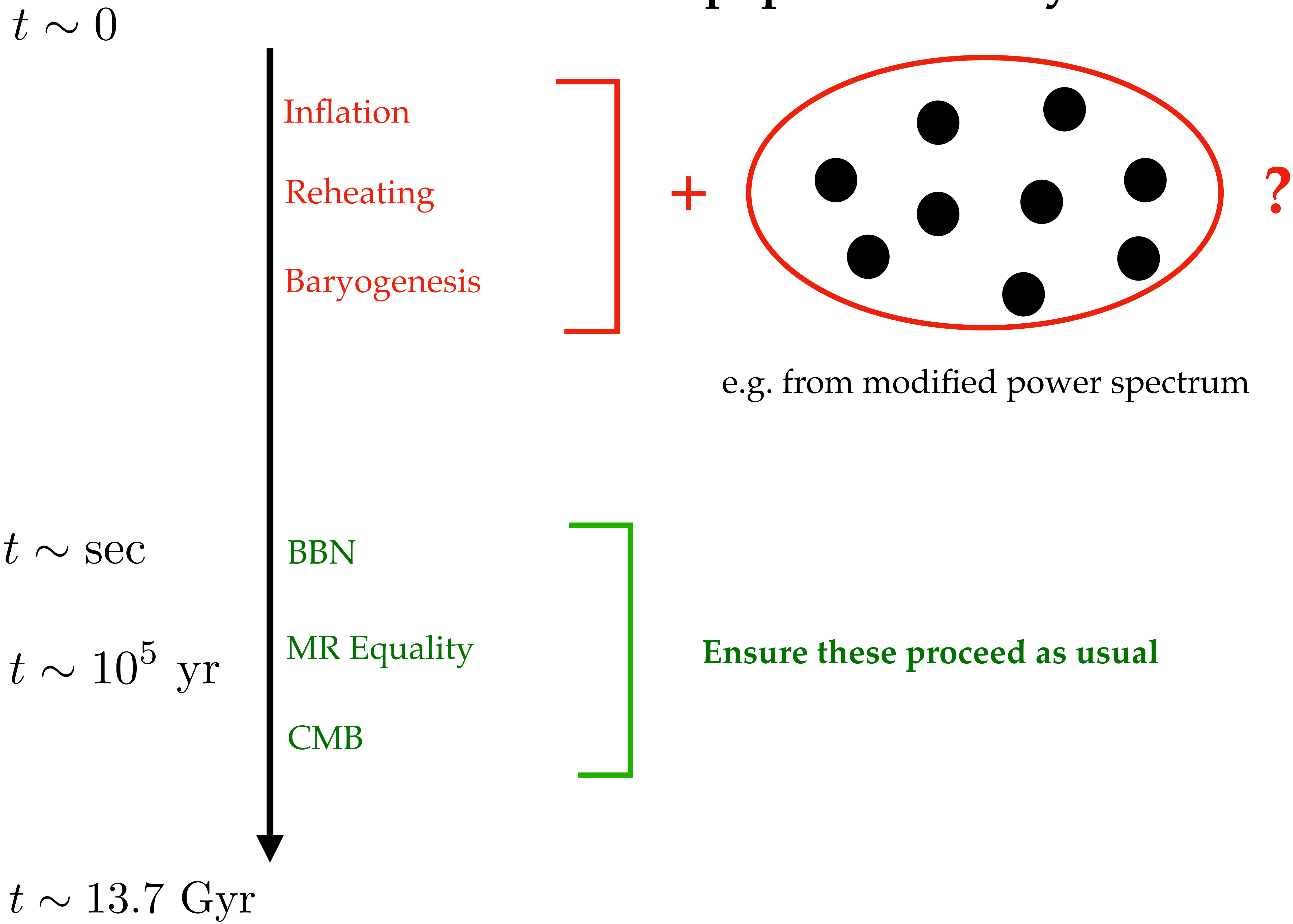
$t \sim 10^5\ \mathrm{yr}$ MR Equality

CMB

Excellent knowledge after ~1 sec

$t \sim 13.7\ \mathrm{Gyr}$

What if we add a PBH population early on?



Overview

Hawking Radiation

Subdominant BH Population

Black Hole Domination

What About Kerr BH?

Overview

Hawking Radiation

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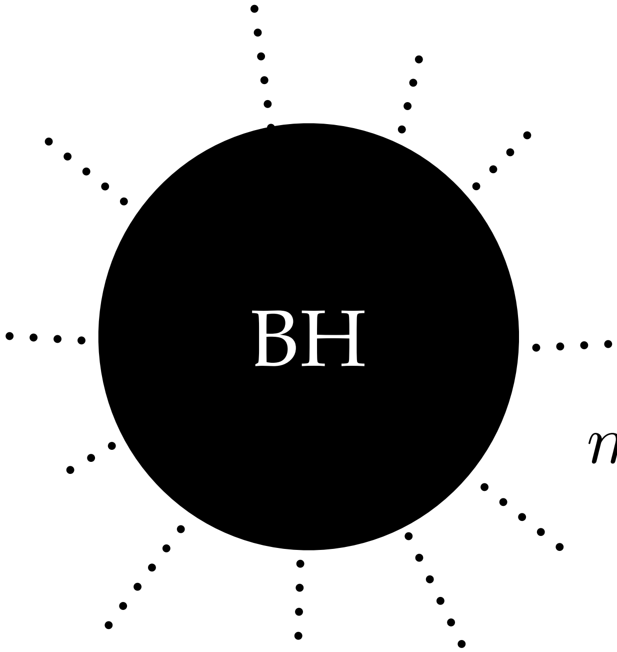
Black Hole Domination

What About Kerr BH?

Hawking Radiation

$i = \mathrm{SM} + \mathrm{DM} + \mathrm{axion} + \cdots$



i

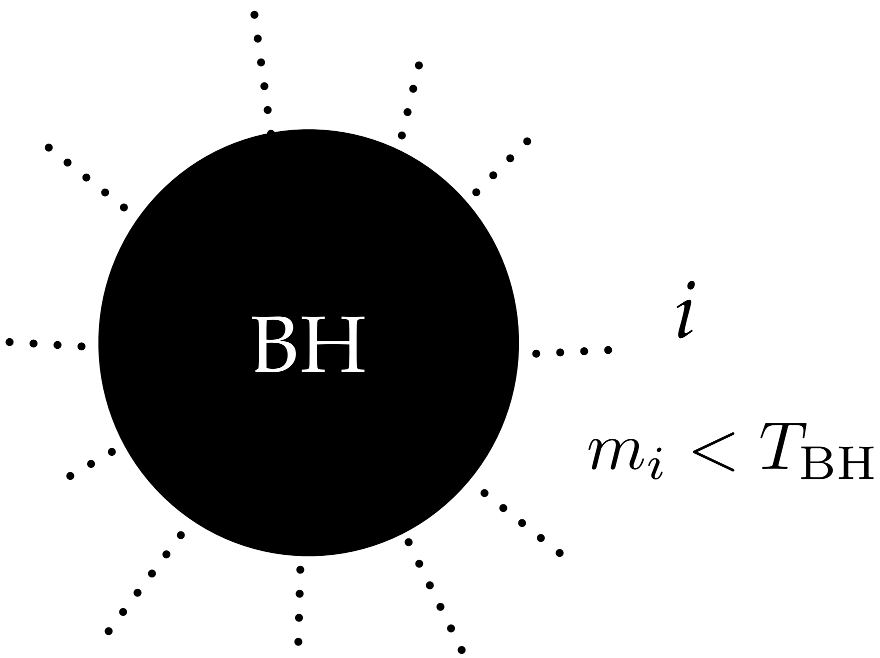
$m_i < T_{\rm BH}$

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

Hawking, Commun. Math. Phys. 43, 199 (1975)
B. J. Carr, Astrophys. J. 206, 8 (1976).
MacGibbon, Webber, Phys. Rev. D 41, 3052 (1990).

Hawking Radiation

$$i = \mathrm{SM} + \mathrm{DM} + \mathrm{axion} + \cdots$$



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

Equivalence principle: all gravitationally coupled species are produced in hawking radiation

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

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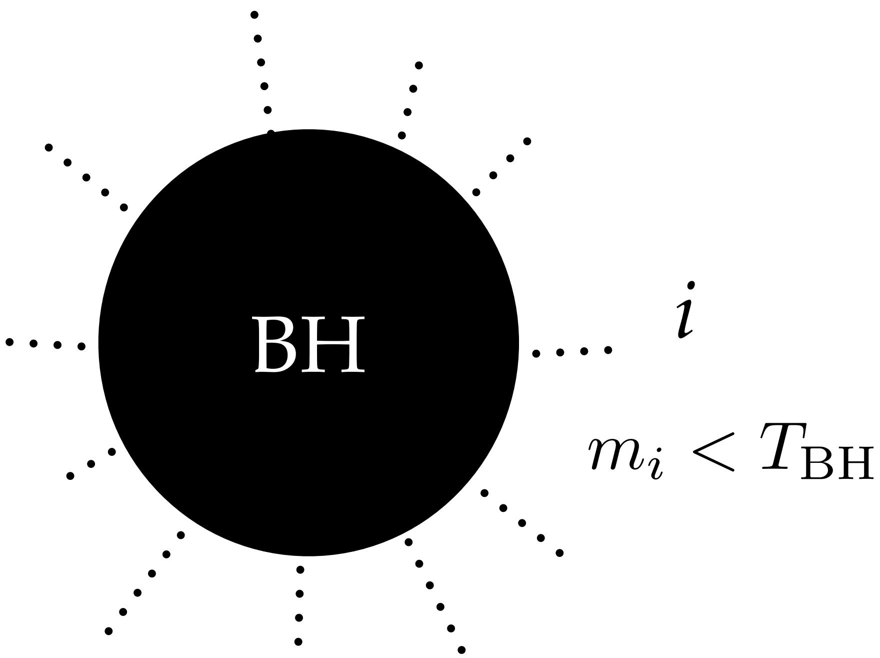
Hawking Radiation



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"Gray body factor" ~ 3.8 (transmission coefficient in curved space)

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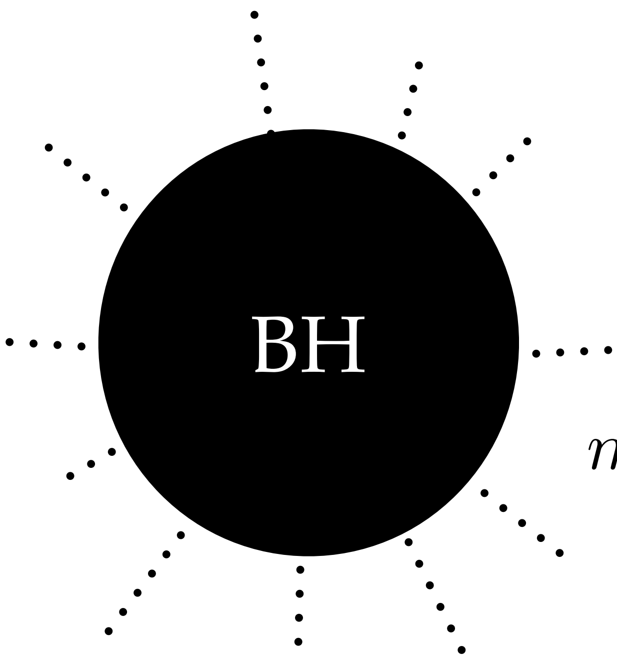
Hawking Radiation



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Not the usual relativistic DOF

$$g_{\star,H}(T_{\mathrm{BH}}) \equiv \sum_i w_i g_{i,H} \quad , \quad g_{i,H} = \begin{cases} 1.82 & s = 0 \\ 1.0 & s = 1/2 \\ 0.41 & s = 1 \\ 0.05 & s = 2 \end{cases}$$

Hawking, Commun. Math. Phys. 43, 199 (1975)
Carr, Astrophys. J. 206, 8 (1976).
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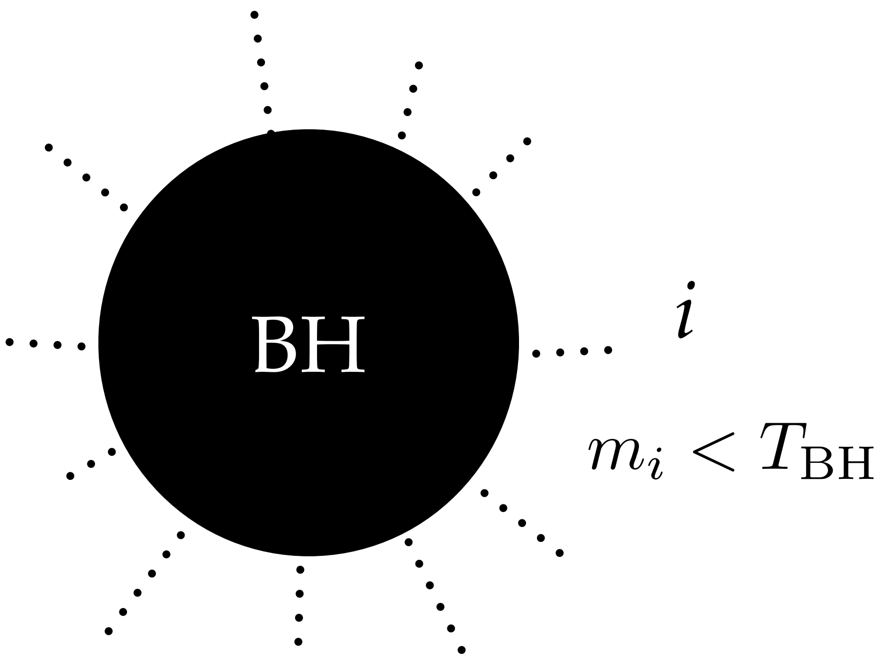
Hawking Radiation



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Unlike particle population: same evaporation time for all BH of same mass!
most particles produced near this time

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

Require full* evaporation before BBN at ~ 1 sec

$\mathrm{NB}: m_{\mathrm{Pl}} \sim \mathrm{mg}$

Overview

Hawking Radiation

Subdominant BH Population

Black Hole Domination

What About Kerr BH?

Subdominant PBH Scenario $f_{\rm BH} \ll 1$

Inflation (same as usual)

SM Reheating
(same as usual)

$$\rho_{{\rm SM},i} = (1 - f_{\rm BH})\rho_{\rm inf}$$

$$\rho_{\rm SM} \propto a^{-4}$$

BH population

$$\rho_{{\rm BH},i} = f_{\rm BH}\rho_{\rm inf}$$

$$\rho_{\rm BH} \propto a^{-3}$$

Assume all BH have the same mass M_0

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Assume all BH have the same mass M_0

BH relative density grows, but never dominates the total energy of the universe

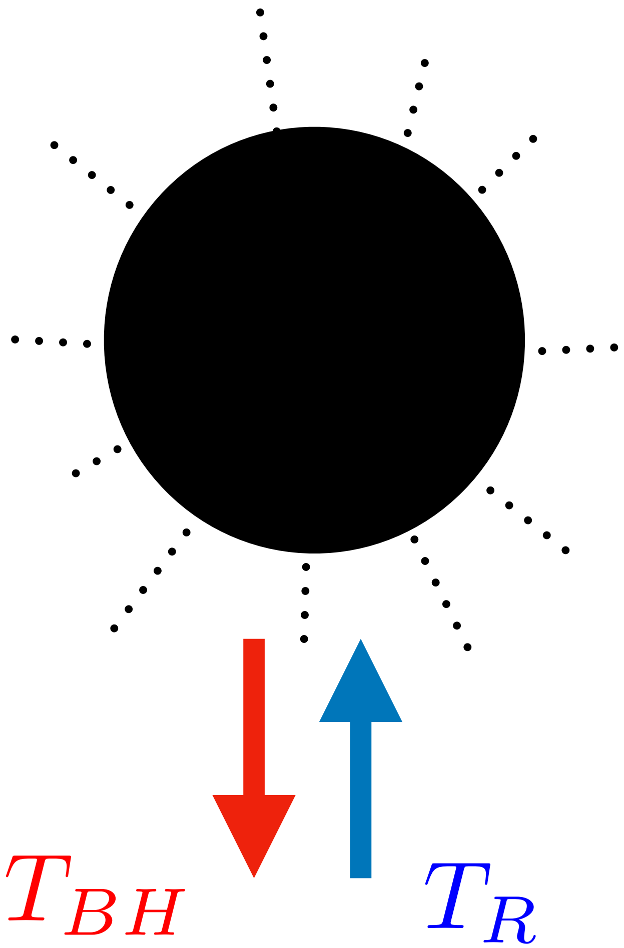
$$H^2 = \left(\frac{\dot a}{a}\right)^2 \propto \rho_{\rm SM}$$

Initial BH yield at reheating

$$Y^0_{\rm BH} = \frac{n_{\rm BH}(t_{\rm RH})}{s(t_{\rm RH})} = \left(\frac{f_{\rm BH}\pi^2 g_*(T_{\rm RH})T^4_{\rm RH}}{30M_0}\right)\left(\frac{45}{2\pi^2 g_*(T_{\rm RH})T^3_{\rm RH}}\right) = \frac{3f_{\rm BH}T_{\rm RH}}{4M_0}$$

Is Background Accretion Important?

If BH are subdominant fraction in background radiation bath with T_R



$$\left.\frac{dM_{\rm BH}}{dt}\right|_{\rm Accretion} = \frac{4\pi\lambda M_{\rm BH}^2\rho_R}{M_{\rm Pl}^4(1+c_s^2)^{3/2}} \qquad \lambda \sim \mathcal{O}(1),\ c_s = \frac{1}{\sqrt{s}}$$

Accretion + Hawking radiation contribution

$$\frac{dM_{\rm BH}}{dt} = \frac{\pi\mathcal{G}g_{*,H}(T_{\rm BH})T_{\rm BH}^2}{480}\left[\frac{\lambda g_*(T_R)}{\mathcal{G}g_{*,H}(T_{\rm BH})(1+c_s^2)^{3/2}}\left(\frac{T_R}{T_{\rm BH}}\right)^4 - 1\right]$$

Combination of factors here satisfies

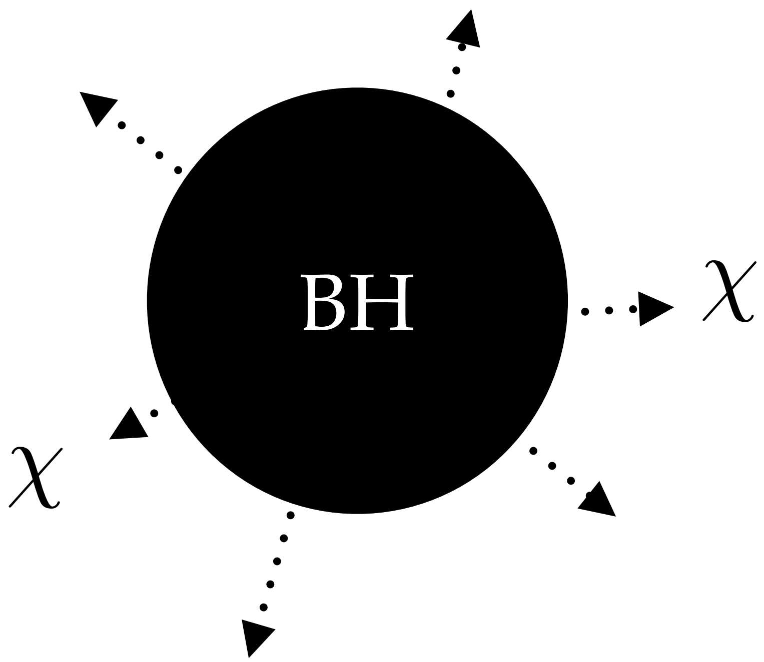
$$\frac{\lambda g_*(T_R)}{(1+c_s^2)^{3/2}} \sim \mathcal{O}(1)$$

Accretion only matters if the radiation bath is hotter than BH

H. Bondi, Mon. Not. Roy. Astron. Soc. 112, 195 (1952)

Massive Particle Production: Dark Matter

$\chi = \mathrm{DM}$



From mass/temperature relation

$$dM_{\mathrm{BH}} = -dE = -\frac{M_{\mathrm{Pl}}^2}{8\pi}\frac{dT_{\mathrm{BH}}}{T_{\mathrm{BH}}^2}$$

dN number of total particles emitted per dT loss

$$dN = \frac{dE}{3T_{\mathrm{BH}}} = \frac{M_{\mathrm{Pl}}^2}{24\pi}\frac{dT_{\mathrm{BH}}}{T_{\mathrm{BH}}^3}$$

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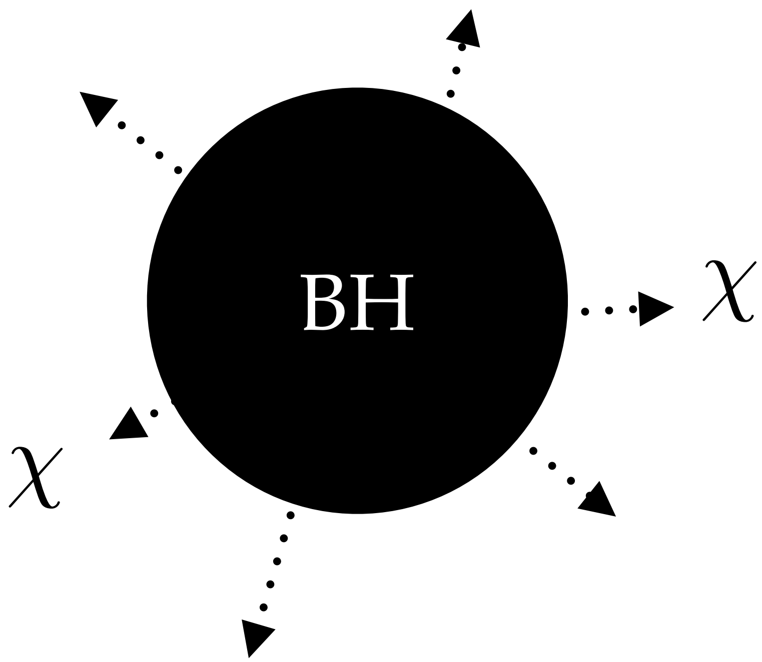

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Including "branching fraction" to DM particles

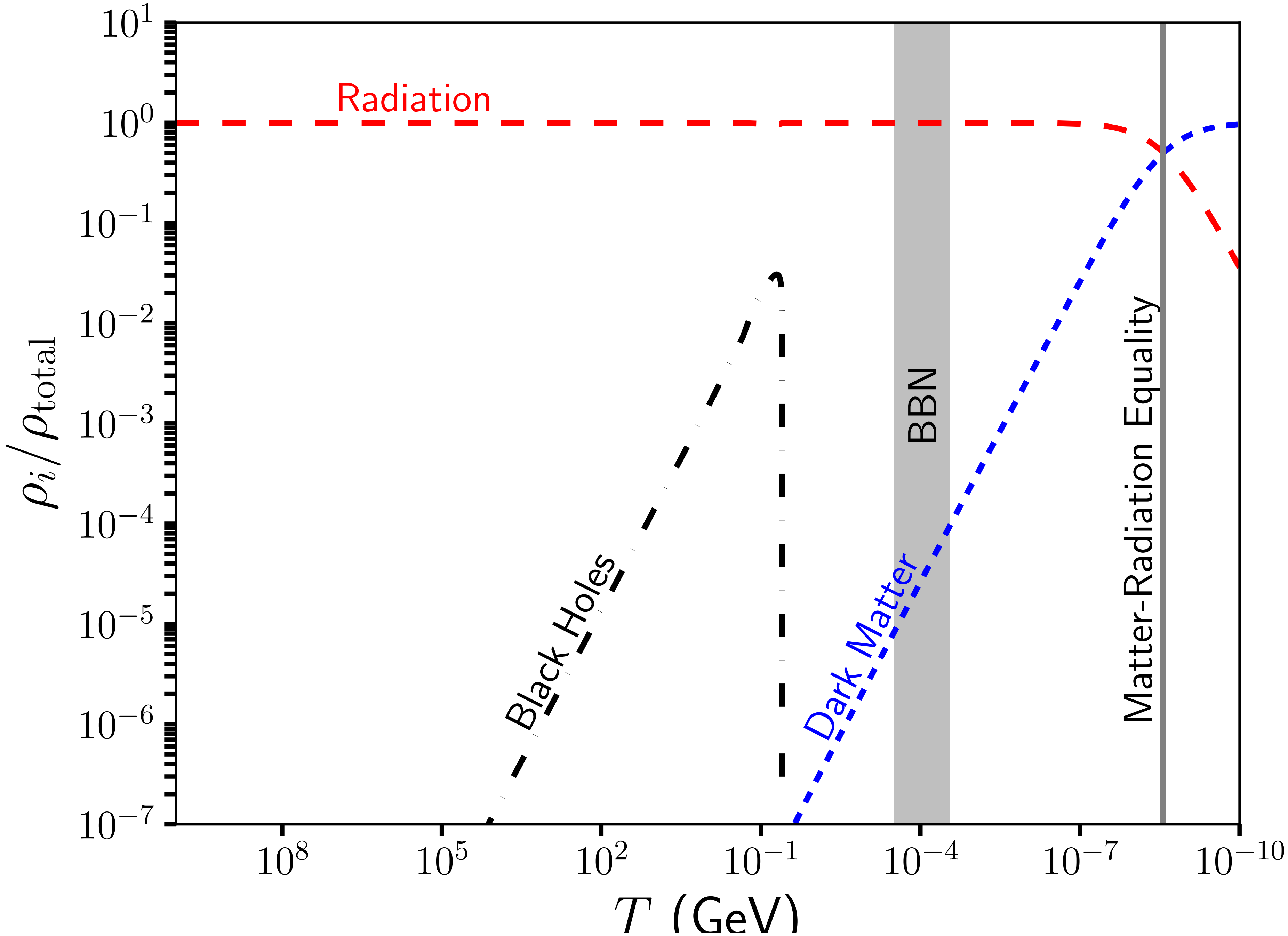
$$dN_\chi = \frac{g_\chi}{g_\star + g_\chi} dN \implies N_\chi = \int_{T_0}^{\infty} dN_\chi = \frac{M_{\mathrm{Pl}}^2}{24\pi}\int_{m_\chi}^{\infty}\frac{dT_{\mathrm{BH}}}{T_{\mathrm{BH}}^3}\frac{g_\chi}{g_\star(T_{\mathrm{BH}}) + g_\chi}$$

Total DM yield $\quad Y_\chi^\infty = N_\chi Y_{\mathrm{BH}}^0 \implies \Omega_\chi = \frac{m_\chi s_0 Y_\chi^\infty}{\rho_{\mathrm{crit}}}$

See also Baumann, Steinhart, Turok 0703250
Lennon, March-Russell, Petrosian-Bryne 1712.07664

Morrison, Profumo 1812.10606

Massive Particle Production: Dark Matter



$$M_{BH,0} = 10^8\,\mathrm{g}$$

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

However BH Generically "Catch Up"

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\left(\frac{\rho_{R,i}}{a^4} + \frac{\rho_{\mathrm{BH},i}}{a^3}\right)$$

Eventual BH Domination for some initial reheat temperature after inflation T_i

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

$$H = \sqrt{\frac{8\pi G \rho_{\mathrm{BH}}}{3}} = \frac{2}{3t}$$

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$$H = \sqrt{\frac{8\pi G \rho_{\mathrm{BH}}}{3}} = \frac{2}{3t}$$

BH evaporation restores SM

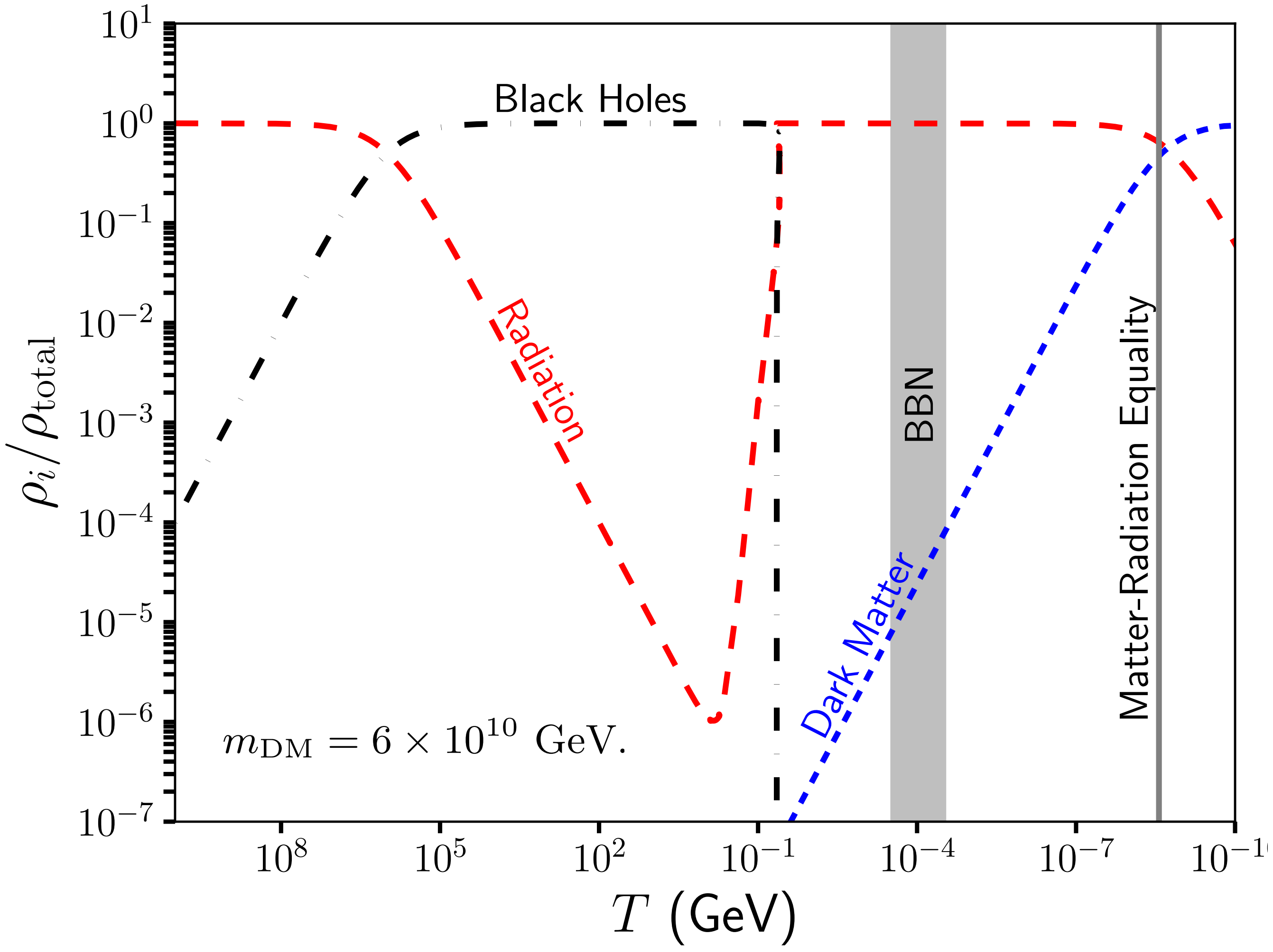
$$\rho_{\mathrm{BH}}(\tau) \propto M_{\mathrm{Pl}}^2 H^2(\tau) = \frac{4M_{\mathrm{Pl}}^2}{9\tau^2} = \frac{\pi^2 g_*}{30} T_{\mathrm{RH}}^4$$

Now insensitive to initial fraction or temperature

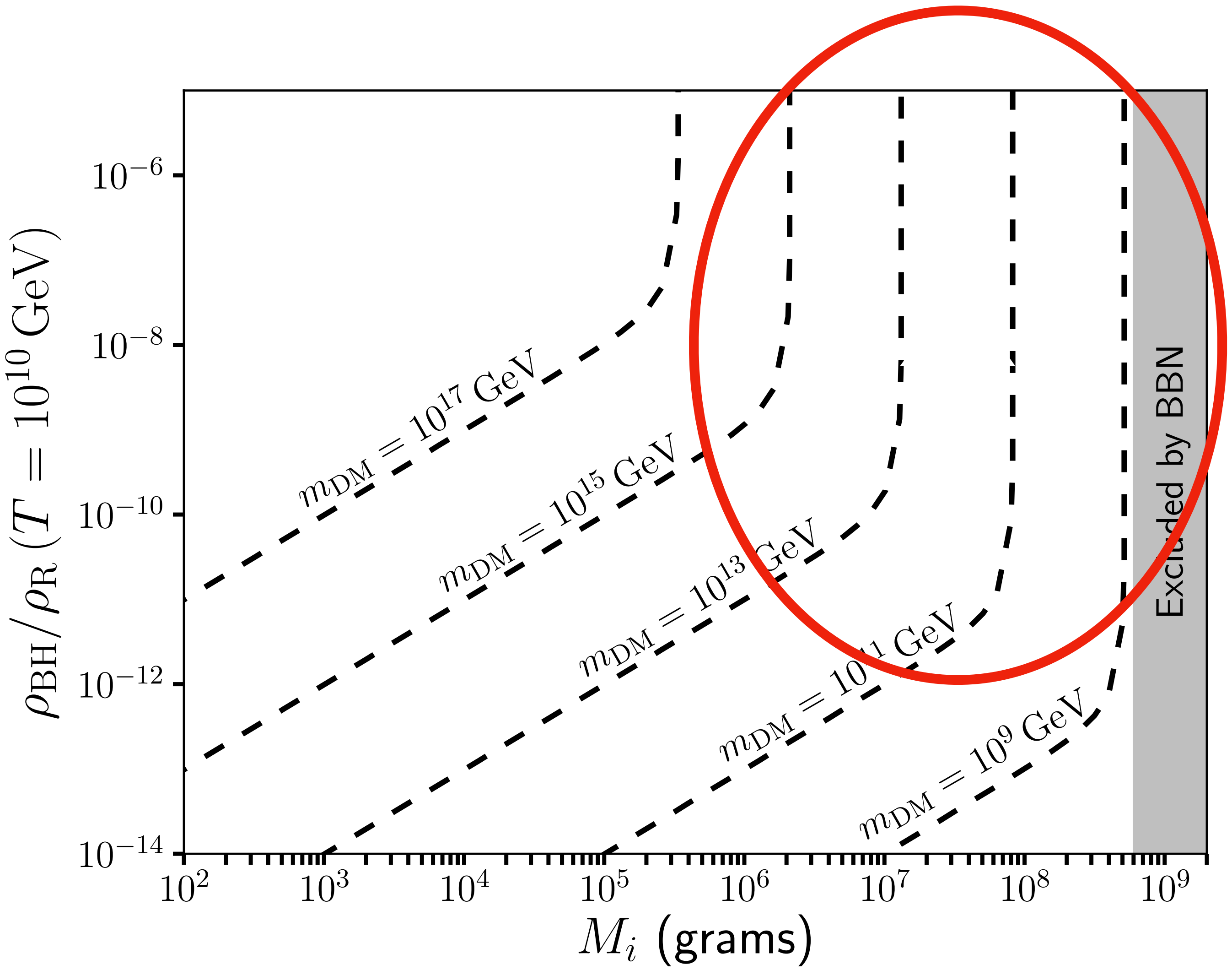
$$T_{\mathrm{RH}} \simeq 50\,\mathrm{MeV}\left(\frac{10^8\,\mathrm{g}}{M_i}\right)^{3/2}\left(\frac{g_{\star,H}(T_{\mathrm{BH}})}{108}\right)^{1/2}\left(\frac{14}{g_\star(T_{\mathrm{RH}})}\right)^{1/4}.$$

"Re-Reheating"

However BH Generically "Catch Up"



BH Domination



Observed DM density on dashed lines
Scenario works mainly with heavy DM

Assuming no additional DM interactions, if BH dominate: $m_{\mathrm{DM}} > 10^9\ \mathrm{GeV}$

Overview

Hawking Radiation

Subdominant BH Population

Black Hole Domination

What About Kerr BH?

Black Hole Domination

Inflation

$\Big\downarrow$ Anything

BH population

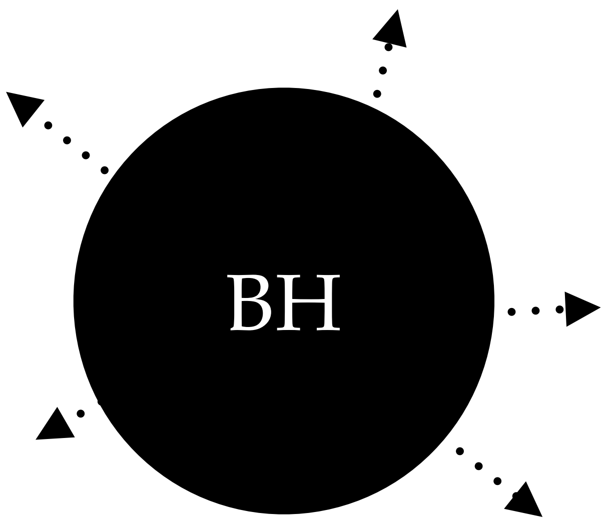
$\Big\downarrow$ Hawking Evaporation

SM + DM + other exotics

Doesn't matter how we get to BH domination could even start as small fraction and "catch up"

Dark Radiation from PBH Domination

Goal: calculate energy density of light BSM particles @ CMB era



SM+DR

$$\Delta N_{\rm eff} \propto \frac{\rho_{\rm DR}(T_{\rm EQ})}{\rho_{\rm SM}(T_{\rm EQ})}$$

System evolves according to

$$\frac{d\rho_{\rm BH}}{dt} = -3\rho_{\rm BH}H + \rho_{\rm BH}\frac{dM_{\rm BH}}{dt}\frac{1}{M_{\rm BH}}$$

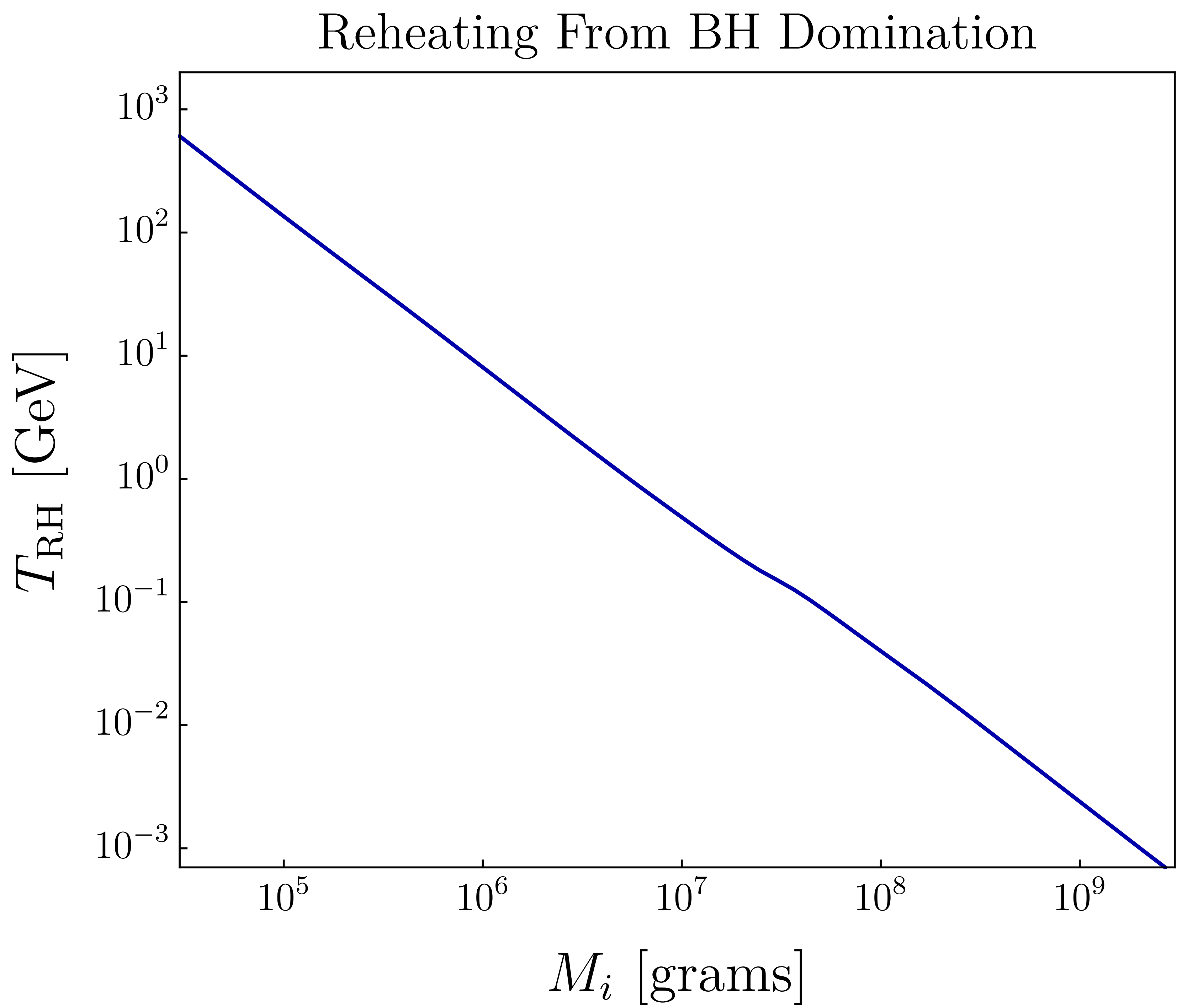
$$\frac{d\rho_{\rm SM}}{dt} = -4\rho_{\rm SM} - \rho_{\rm BH}\frac{dM_{\rm BH}}{dt}\bigg|_{\rm SM}\frac{1}{M_{\rm BH}}$$

$$\frac{d\rho_{\rm DR}}{dt} = -4\rho_{\rm DR} - \rho_{\rm BH}\frac{dM_{\rm BH}}{dt}\Big|_{\rm DR}\frac{1}{M_{\rm BH}}$$

DR density integrable

Dark Radiation from PBH Domination

Step 1: Create the full SM radiation bath at the BH evaporation time



RH temperature of the SM bath once BH are gone

Dark Radiation from PBH Domination

Step 2: Determine SM radiation density at matter-radiation equality

Entropy conservation

$$(a^3 s)_{\rm RH} = (a^3 s)_{\rm EQ} \implies a_{\rm RH}^3\, g_{\star,S}(T_{\rm RH})\, T_{\rm RH}^3 = a_{\rm EQ}^3\, g_{\star,S}(T_{\rm EQ})\, T_{\rm EQ}^3$$

Entropic DOF (not to be confused with Hawking evaporation DOF)

$$\frac{T_{\rm EQ}}{T_{\rm RH}} = \left(\frac{a_{\rm RH}}{a_{\rm EQ}}\right)\left(\frac{g_{\star,S}(T_{\rm RH})}{g_{\star,S}(T_{\rm EQ})}\right)^{1/3} \qquad T_{\rm EQ} = 0.75\,{\rm eV}$$

Dark Radiation from PBH Domination

Step 2: Determine SM radiation density at matter-radiation equality

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$$(a^3 s)_{\rm RH} = (a^3 s)_{\rm EQ} \implies a^3_{\rm RH}\, g_{\star,S}(T_{\rm RH})\, T^3_{\rm RH} = a^3_{\rm EQ}\, g_{\star,S}(T_{\rm EQ})\, T^3_{\rm EQ}$$

Entropic DOF (not to be confused with Hawking evaporation DOF)

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SM Temperature ratio and energy density @EQ

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

Dark Radiation from PBH Domination

Step 3: calculate the ratio of dark/visible radiation

No entropy dumps in DR

$$\frac{\rho_{\rm DR}(T_{\rm EQ})}{\rho_{\rm DR}(T_{\rm RH})} = \left(\frac{a_{\rm RH}}{a_{\rm EQ}}\right)^4$$

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$$\frac{\rho_{\mathrm{DR}}(T_{\mathrm{EQ}})}{\rho_{\mathrm{DR}}(T_{\mathrm{RH}})} = \left(\frac{a_{\mathrm{RH}}}{a_{\mathrm{EQ}}}\right)^4$$

Ratio to SM set by Hawking DOF

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

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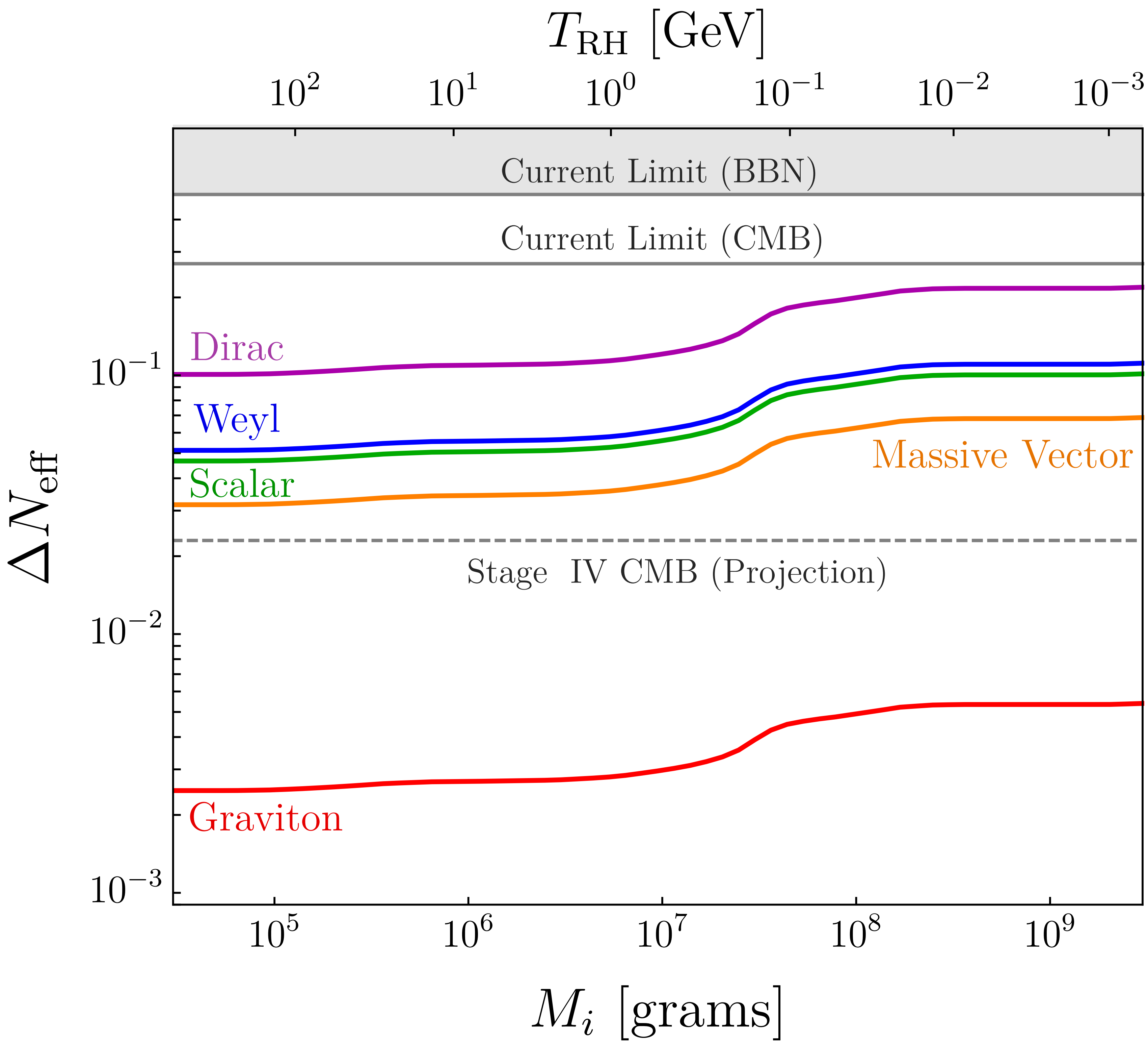
Final result *milder* than naive expectation

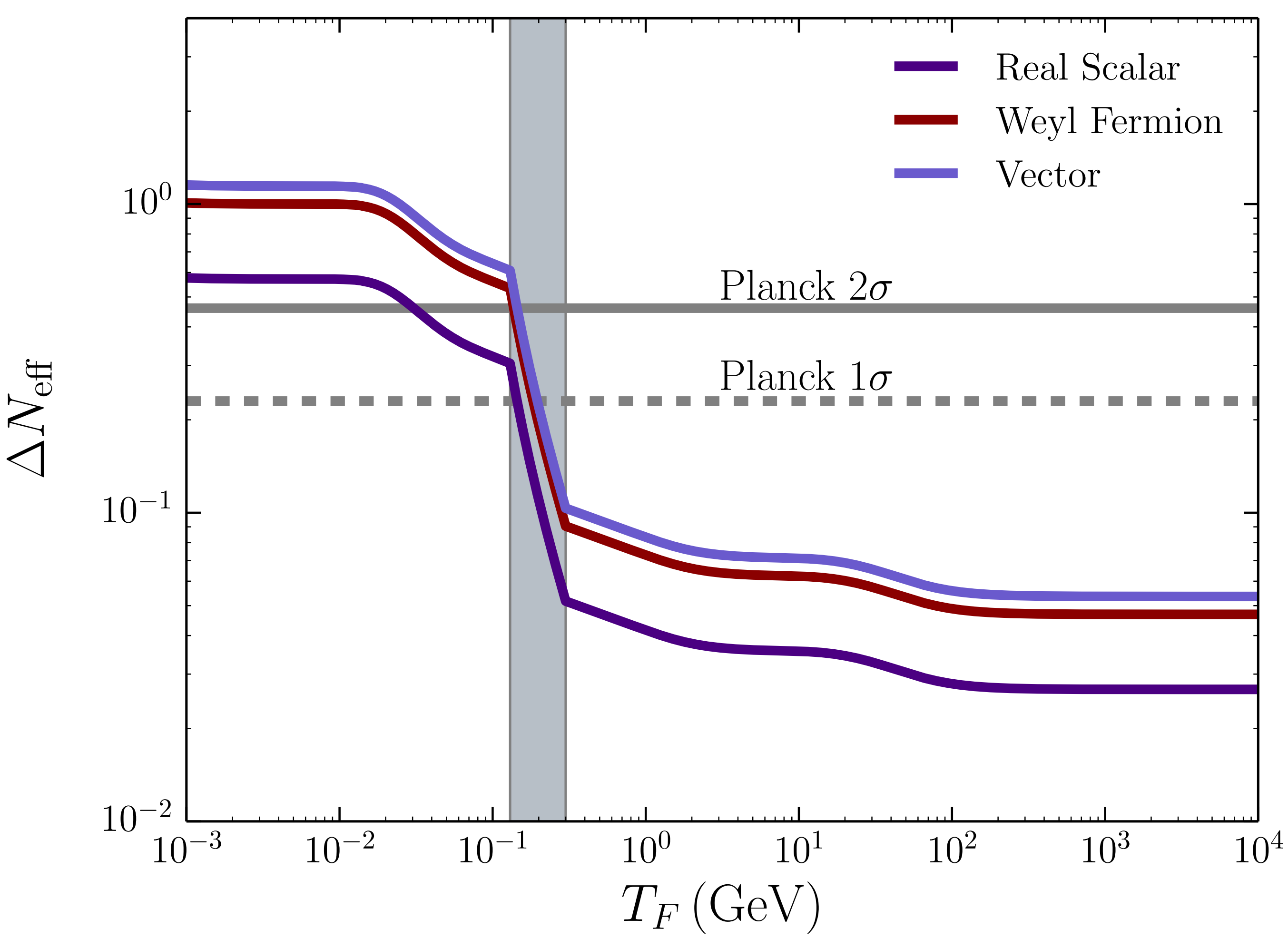
$$\boxed{\Delta N_{\rm eff} = \frac{\rho_{\rm DR}(T_{\rm EQ})}{\rho_{R}(T_{\rm EQ})}\left[N_\nu + \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\right] \approx 0.10\left(\frac{g_{{\rm DR},H}}{4}\right)\left(\frac{106}{g_\star(T_{\rm RH})}\right)^{1/3}}$$

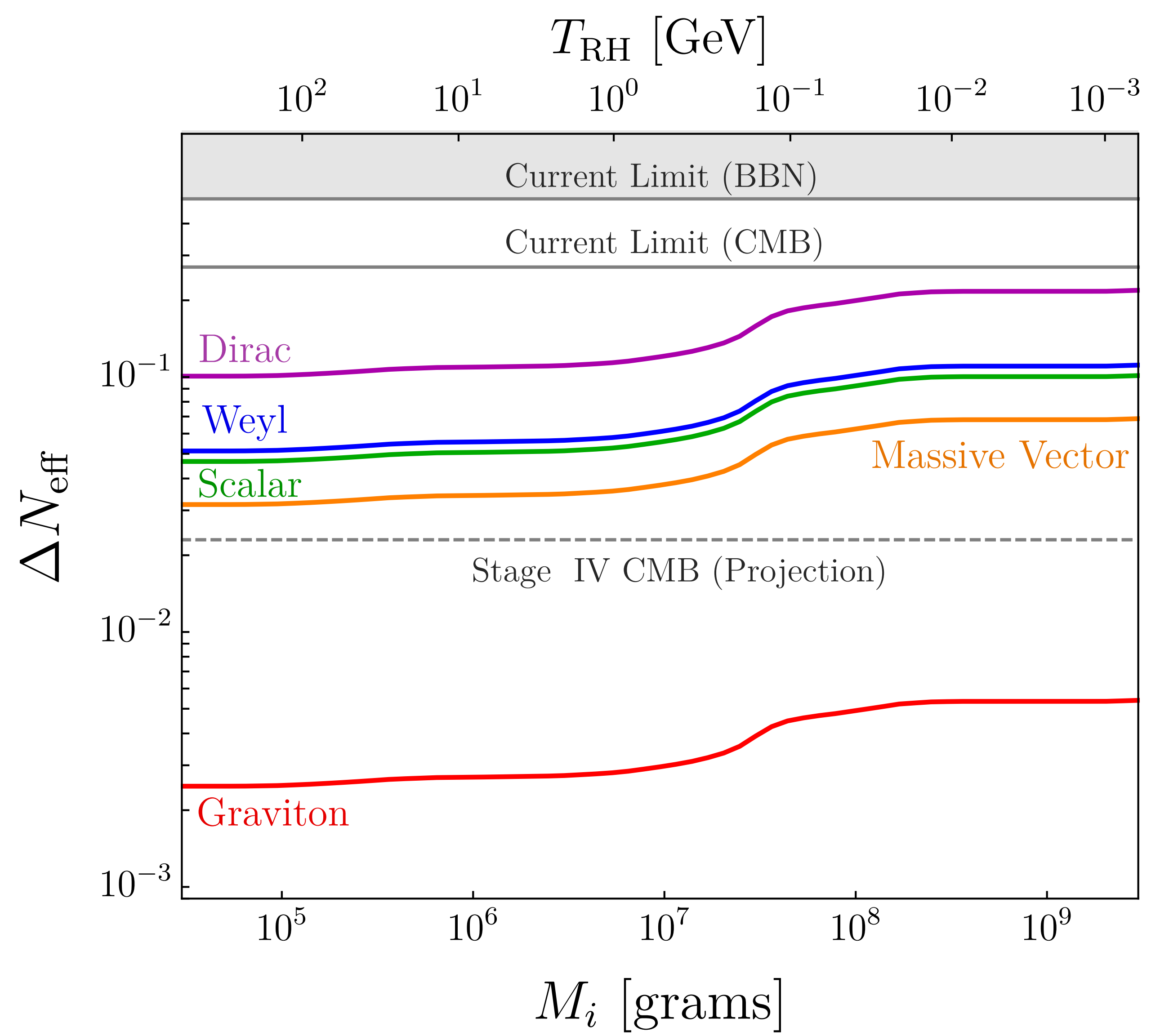
BH is hotter than RH temp —> smaller branching to DS

Neff in BH Domination



Comparing to Thermal Relics

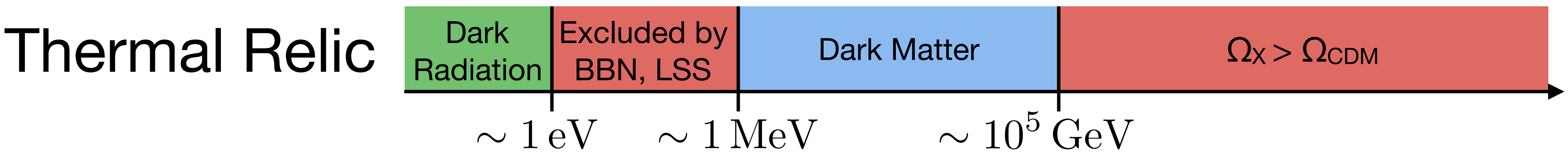




Flaugher et. al. CMBS4 science book

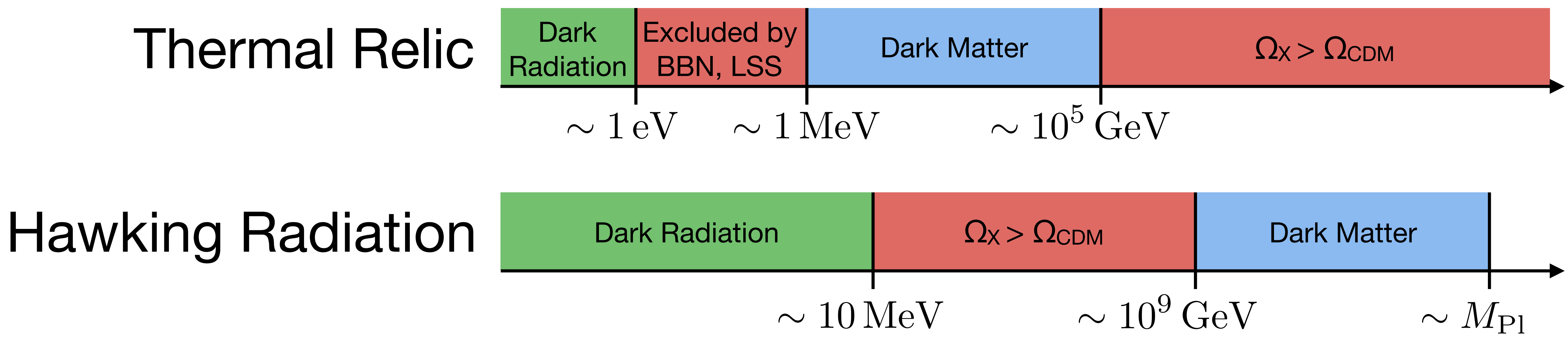
Unlike relics, for BH, all DR is within interesting range for future CMB S4 which will measure this at few % level

Comparing to Thermal Relics



Usual picture of particles in thermal equilibrium

Comparing to Thermal Relics



From BH domination, note that heavier masses can count as radiation!

b/c typically emitted at higher energies than the SM bath

[Assumes that the dark radiation does not thermalize with the SM]

Overview

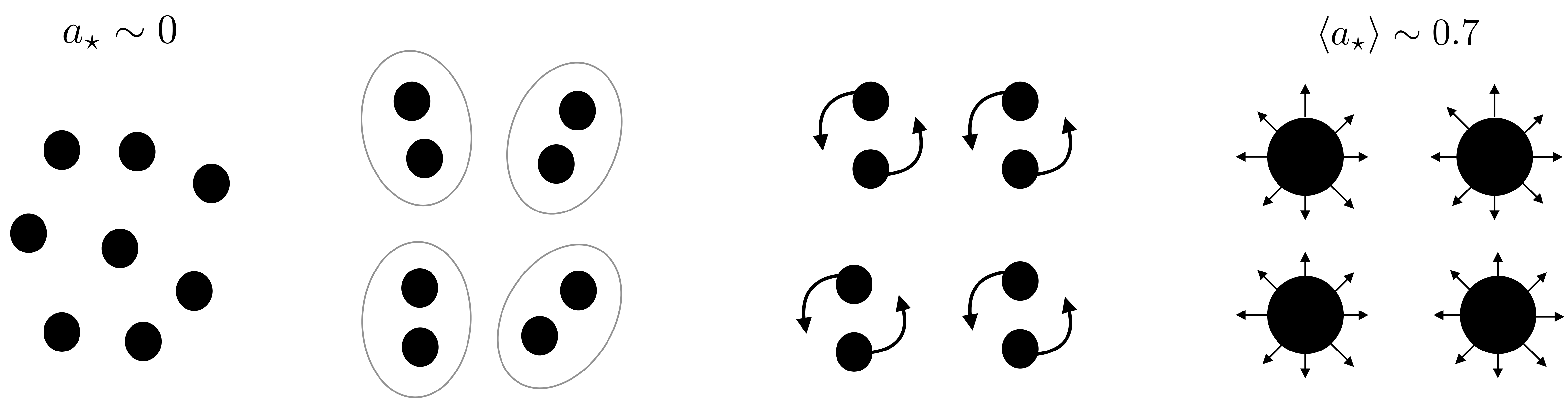
Hawking Radiation

Subdominant BH Population

Black Hole Domination

What About Kerr BH?

Mergers Spin Up BH —> Kerr BH



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

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

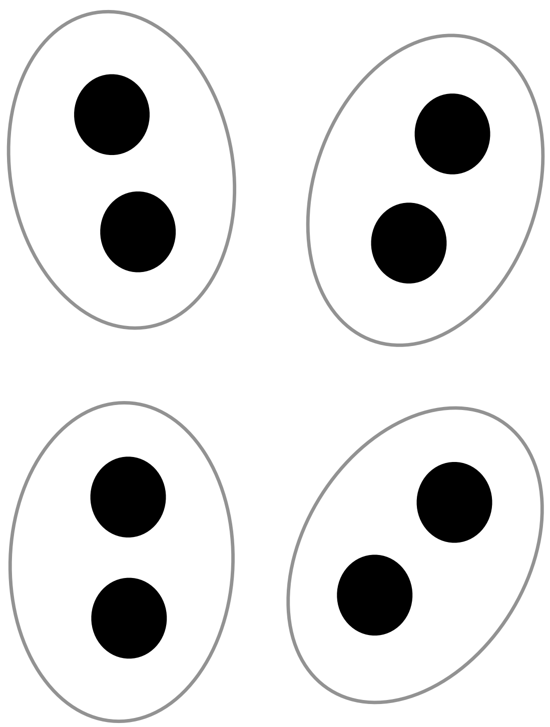
3. Mergers
$\rho_{\rm BH} \sim \rho_{\rm tot}$
$\rho_{\rm GW} \to \Delta N_{\rm eff,GW}$

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

$\Delta N_{\rm eff}$ from *both* GW and from Hawking radiation of gravitons

$$\mathbf{S_i} = a_i \frac{G m_i^2}{c} \hat{\mathbf{S}}_\mathbf{i},$$ spin parameter

Binary Capture Criteria



2. Binary Capture

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

Cross section Quinlan, Shapiro 1989

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

Does capture occur in a Hubble time?

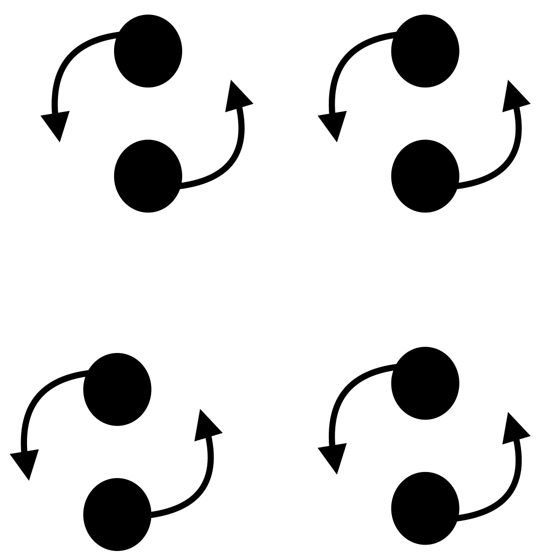
$$\frac{\Gamma_{\rm C}}{H} \simeq 45\sqrt{\frac{3}{8\pi\rho_{\rm T}}}\frac{M}{M_{\rm P}^3}\frac{\rho_{\rm BH}}{v^{11/7}} \qquad \Gamma_{\rm C} \equiv n_{\rm BH}\sigma_{\rm C} v$$

If so, capture freeze-out occurs when

$$T_{\rm eff}(a_{\rm CF}) \approx 2.6\times 10^9\ {\rm GeV}\left(\frac{v}{10^{-3}}\right)^{11/14}\left(\frac{10^8\ {\rm g}}{M_i}\right)^{1/2} f_{\rm BH}(a_{\rm CF})^{-1/2}$$

$$H \equiv 1.66\sqrt{g_\star}\frac{T_{\rm eff}^2}{M_{\rm P}}$$

Inspirals and Dark Radiation



3. Mergers

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

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

Inspiral timescale (circular orbit)

$$t_{\rm I} = \frac{5M_{\rm P}^6}{512M^3}\frac{\lambda^4}{n_{\rm BH}^{4/3}(a_{\rm CF})}$$

parametrize ignorance

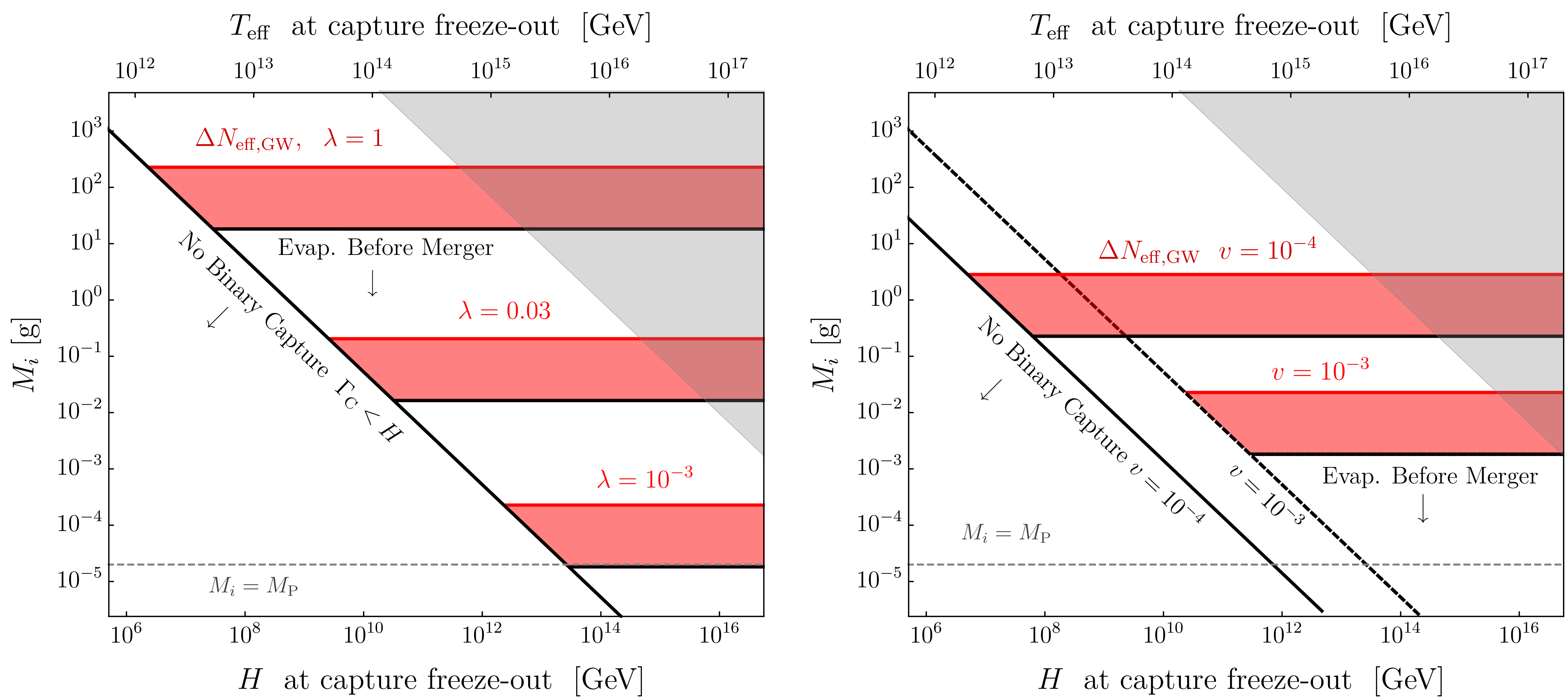
Demand inspiral before evaporation

$$M \gtrsim 0.2\,{\rm g}\left(\frac{235}{\langle \ell^{-1}\rangle}\right)^{1/2}\left(\frac{\lambda}{0.1}\right)^2\left(\frac{10^{-3}}{v}\right)^{44/21} f_{\rm BH}(a_{\rm CF})^{2/3}$$

Dark radiation from GW energy density

$$\Delta N_{\rm eff,GW} = \frac{\rho_{\rm GW}(t_{\rm EQ})}{\rho_{\rm R}(t_{\rm EQ})}\left[\frac{8}{7}\left(\frac{11}{4}\right)^{4/3} + N_\nu\right] \quad \propto (t_{\rm I}/\tau)^{2/3}$$

Dark Radiation From Gravitational Waves



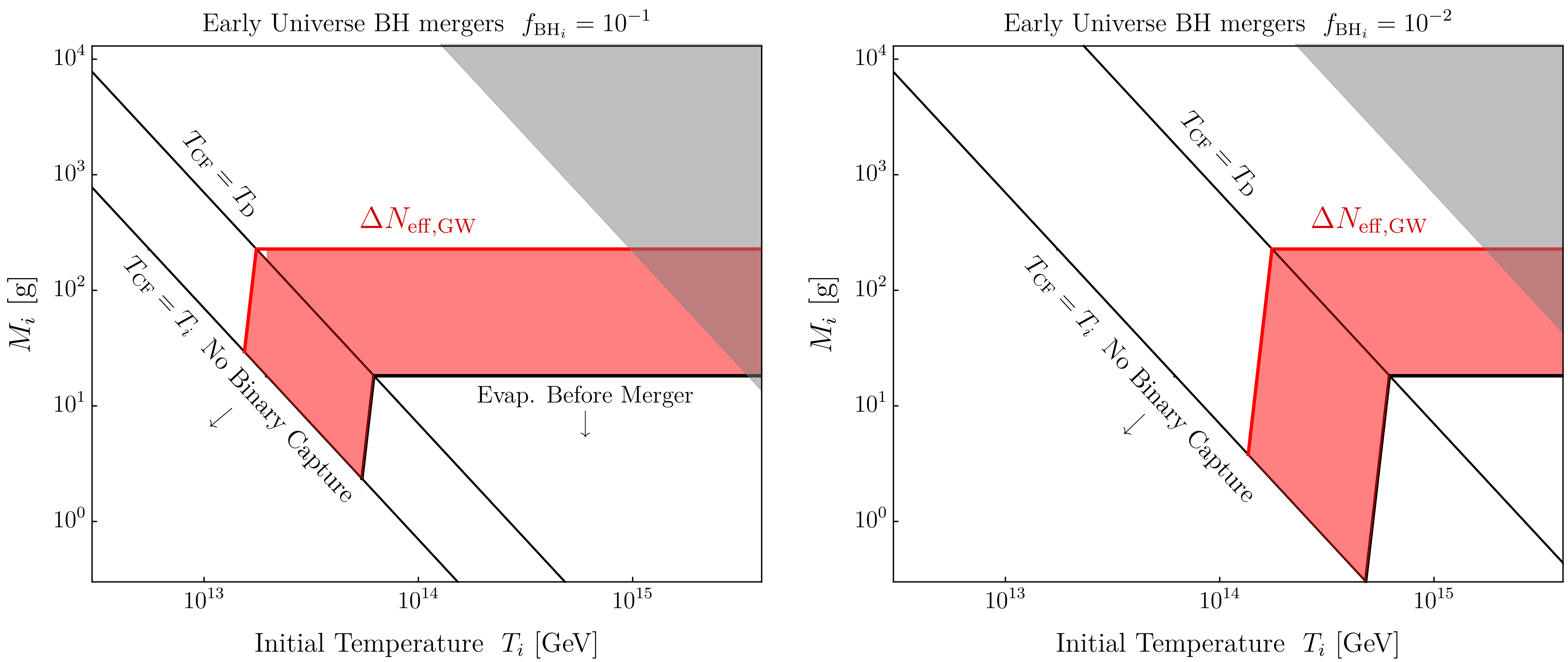
Assumes PBH give ~ 10% of energy to GW

$$H \equiv 1.66\sqrt{g_\star}\frac{T_{\rm eff}^2}{M_{\rm P}}$$

Observable window

$\Delta N_{\rm eff} = 10^{-2} - 0.5$

Dark Radiation From Gravitational Waves

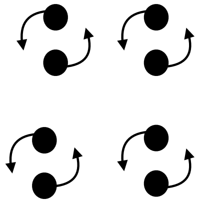


Same as before, just in terms of initial params before PBH domination

$$H \equiv 1.66\sqrt{g_\star}\frac{T_{\mathrm{eff}}^2}{M_{\mathrm{P}}}$$

Observable window

$$\Delta N_{\mathrm{eff}} = 10^{-2} - 0.5$$

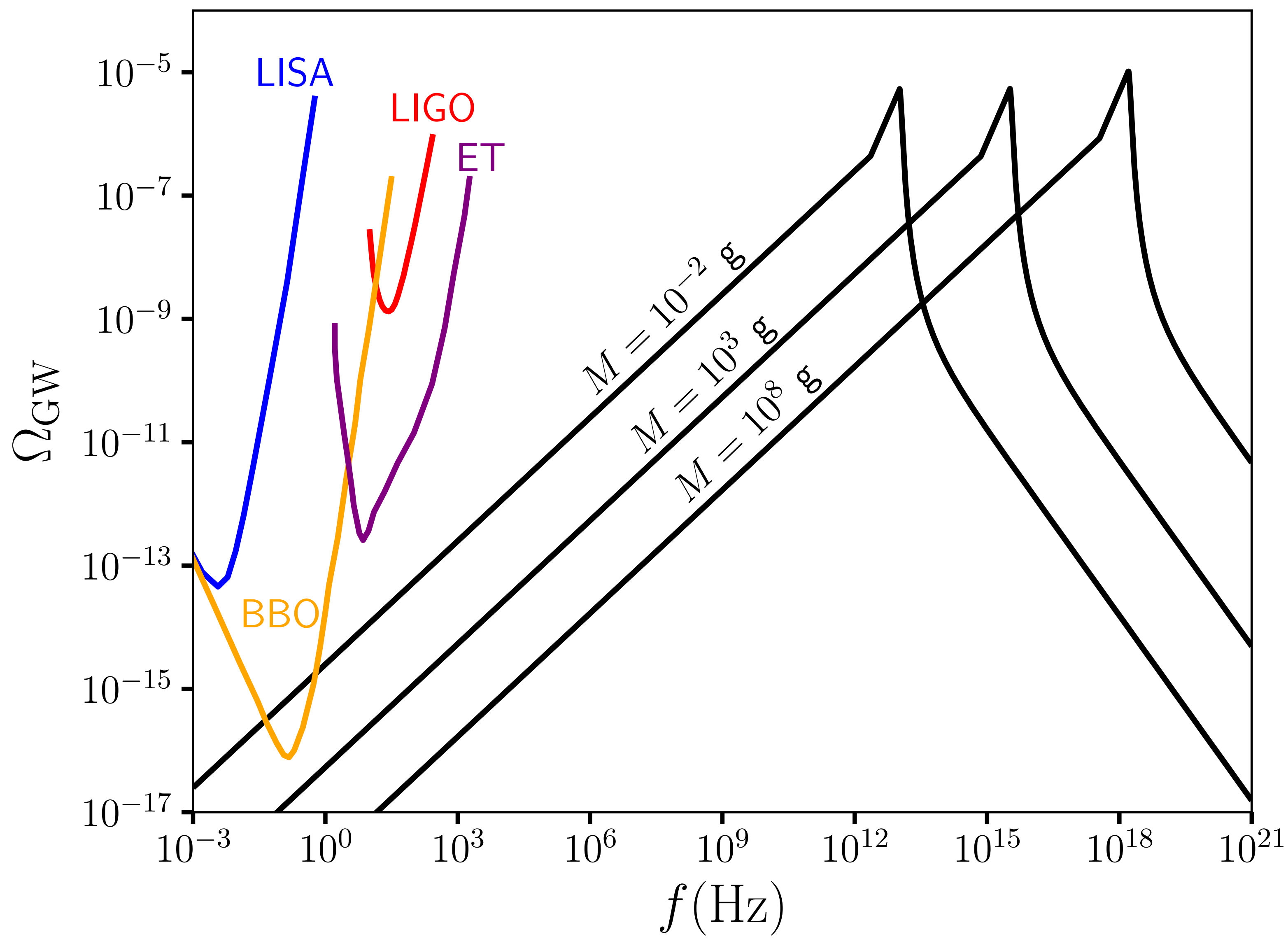


3. Mergers

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

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

Gravitational Waves From PBH Mergers

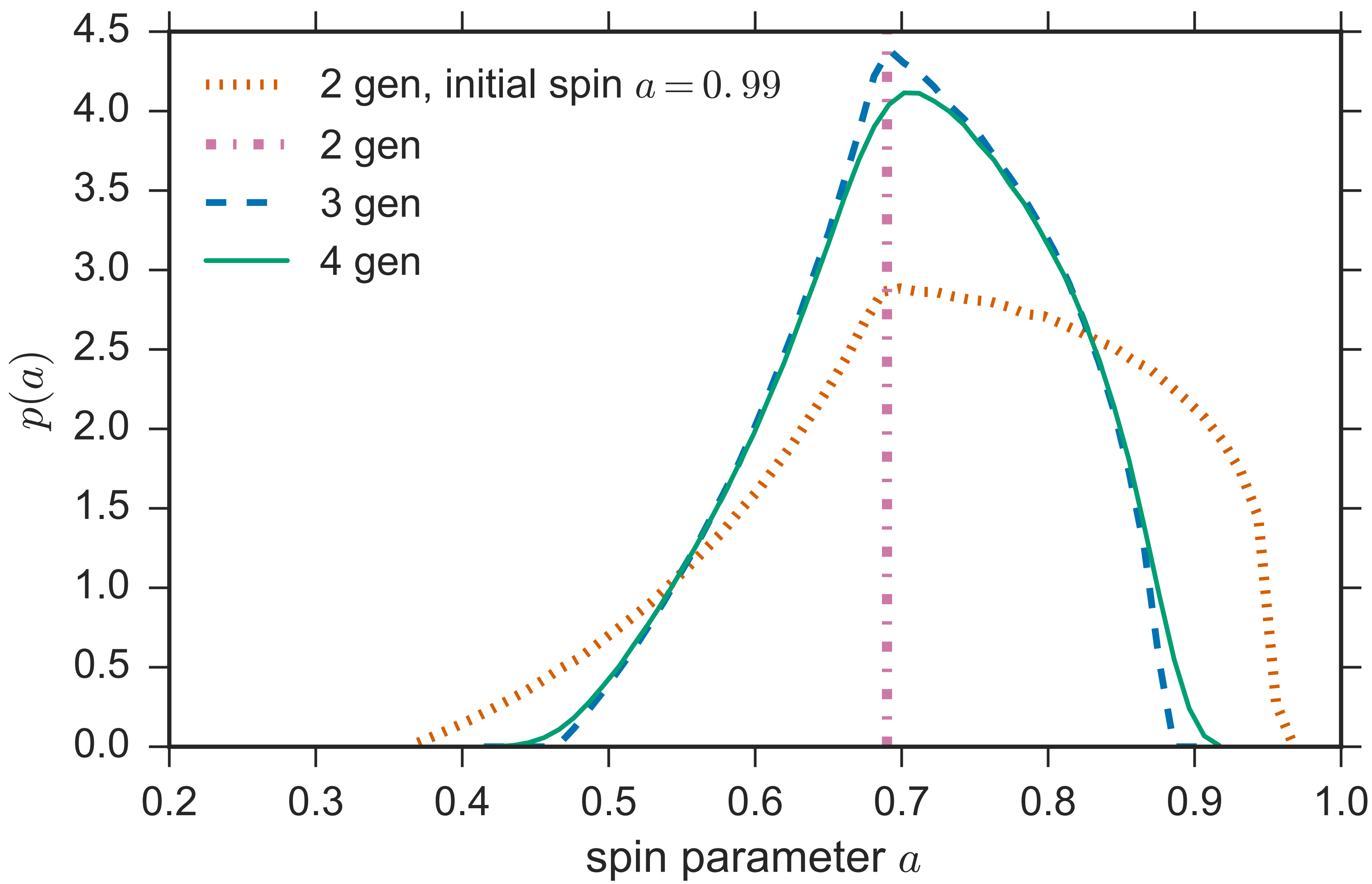


Irreducible GW prediction, but you have to be lucky

Spectra assume merger just before evaporation

…otherwise suppression ~ $(t_{\rm I}/\tau)^{2/3}$

Mergers Also Induce PBH Spin



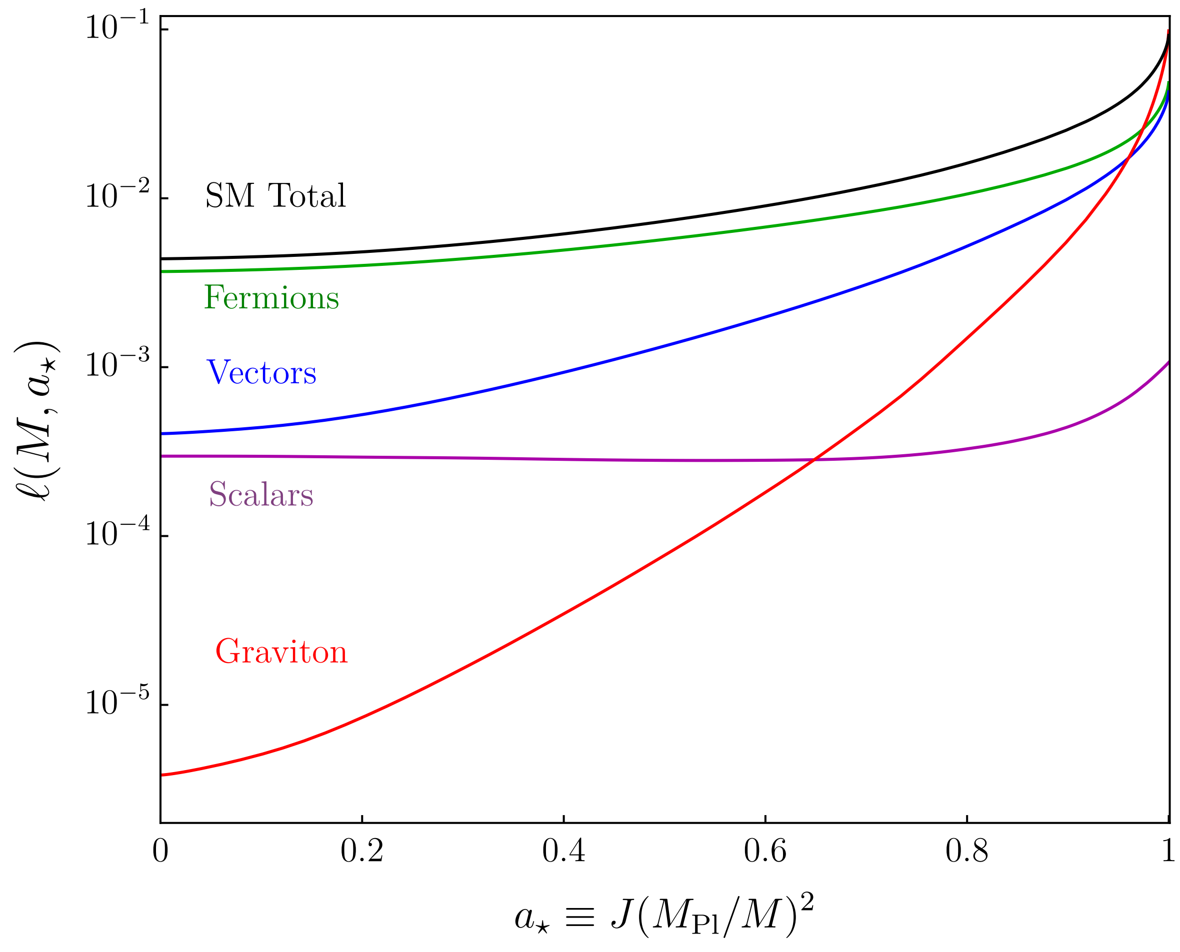
$$\mathbf{S_i} = a_i \frac{G m_i^2}{c} \hat{\mathbf{S}}_{\mathbf{i}},$$

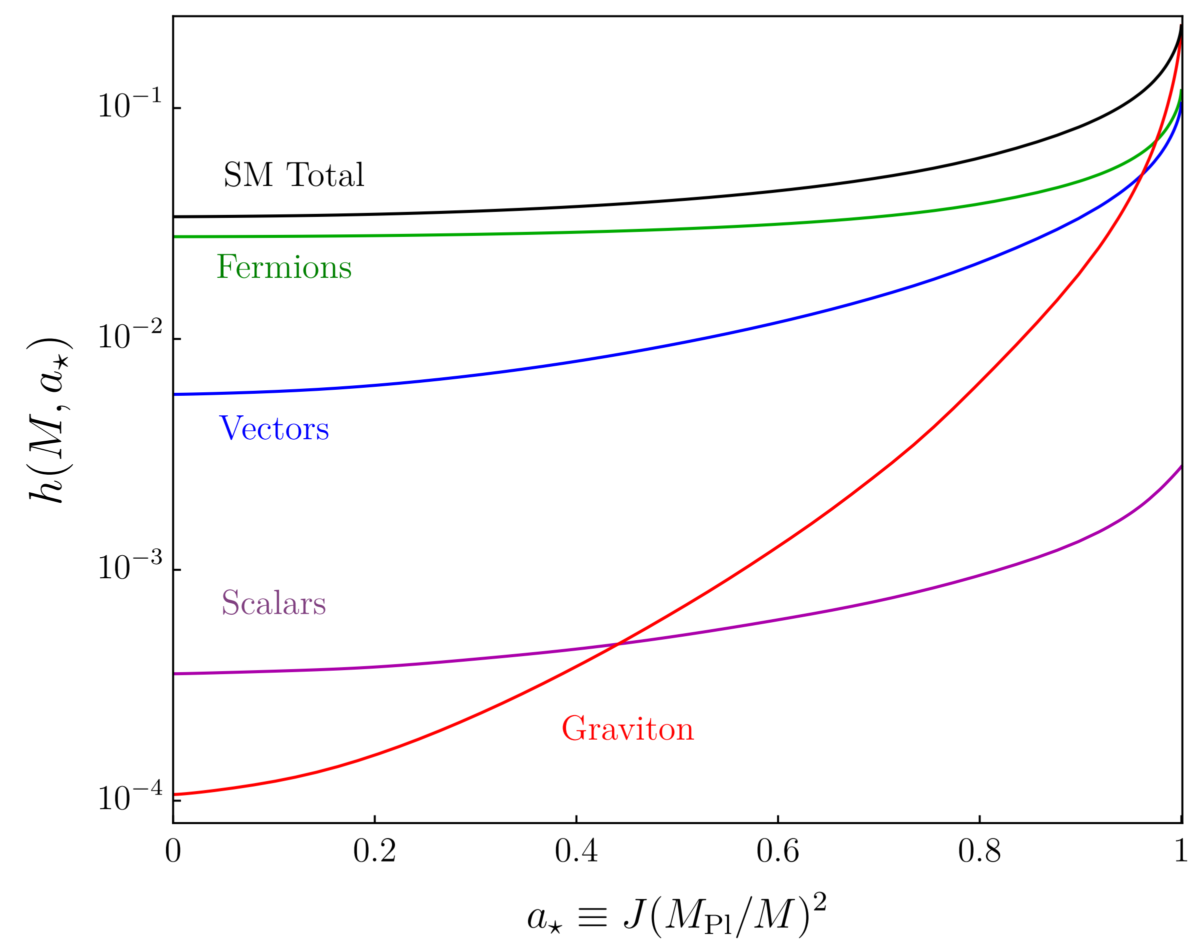
Feshbach, Holtz, Farr 1703.06869

BH Spin Changes Hawking Evaporation

Need to track mass and spin loss

$$\frac{dM}{dt} = -\ell(M, a_\star)\,\frac{M_{\rm P}^4}{M^2}, \qquad \frac{dJ}{dt} = -h(M, a_\star)J\,\frac{M_{\rm P}^4}{M^3}$$

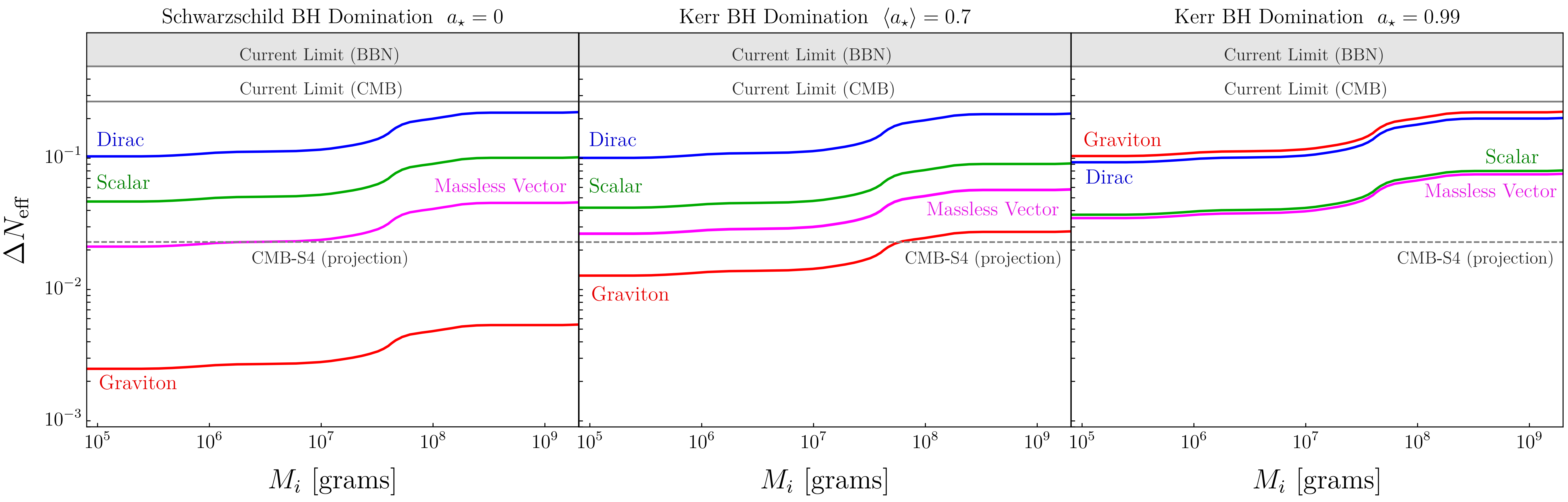




Higer spin BH prefer to emit gravitons as Hawking radiation!

Page PRD (1976)

Dark Radiation from Kerr PBH Evaporation



Near extremal —> hot relic graviton background

Concluding Remarks

1) We don't know what happened before BBN

2) Early BH population: evaporation can seed initial conditions for BBN

3) Can produce super heavy DM and exotic particles (added Neff)

4) Mergers induce Kerr PBH population

Neff and Gravitational Waves (mergers)
Neff from relic gravitons (evaporation)

Other possibilities:

Modified structure formation (Erickeck 2015)?
Vary distribution of BH masses?

Thanks!