Dark Matter & Radiation From Black Hole Domination

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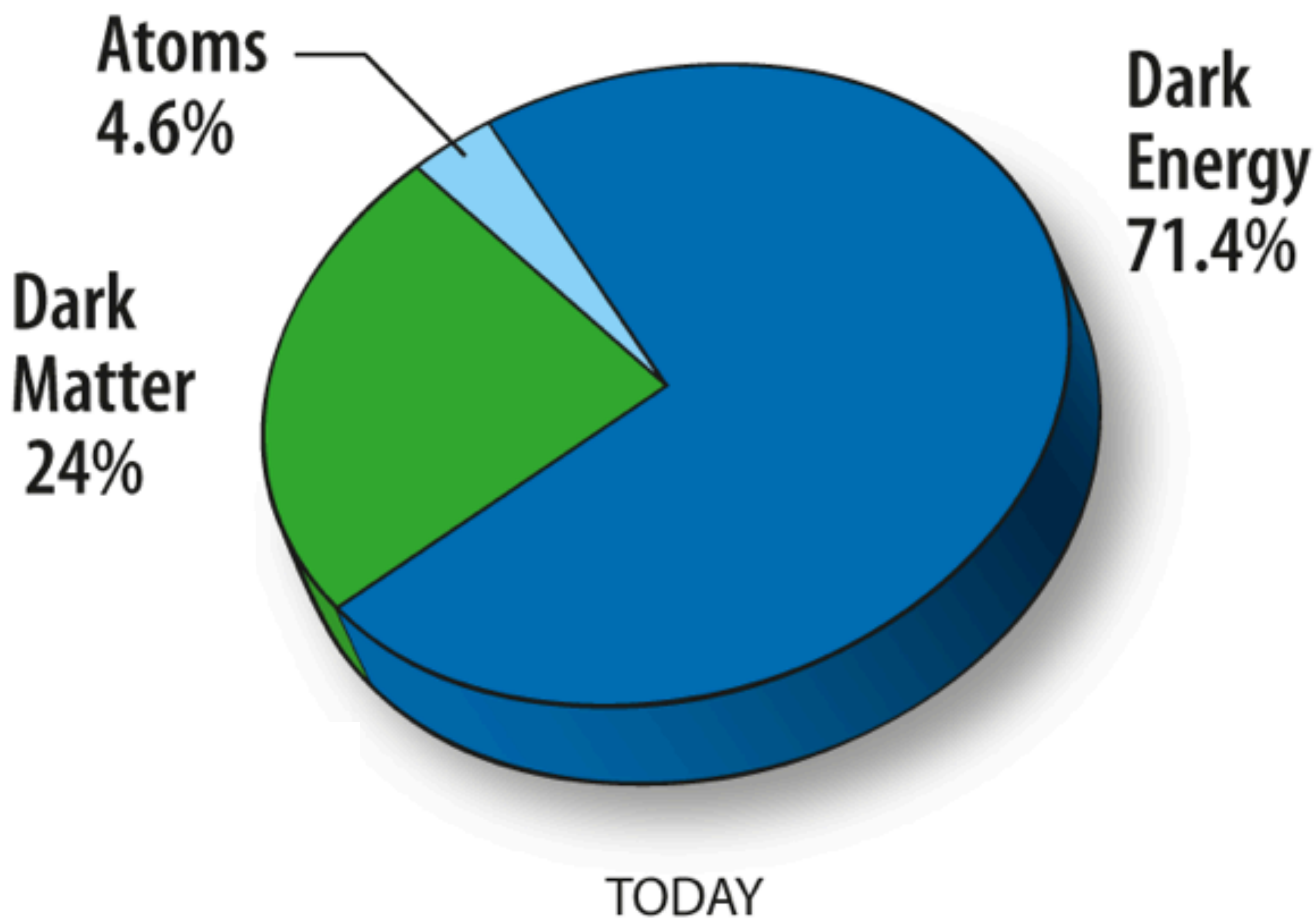
Fermilab

with Dan Hooper and Sam McDermott 1905.01301 [JHEP]

University of Wisconsin, Madison Dec 11, 2019

Outstanding Fundamental Questions in Physics

Matter Asymmetry
Inflation
Neutrino Masses



Accelerated Cosmic Expansion

Hubble Tension?

Also Quantum Gravity

Overview

Standard Cosmology: The Lore

Hawking Radiation

Subdominant BH Population

Black Hole Domination

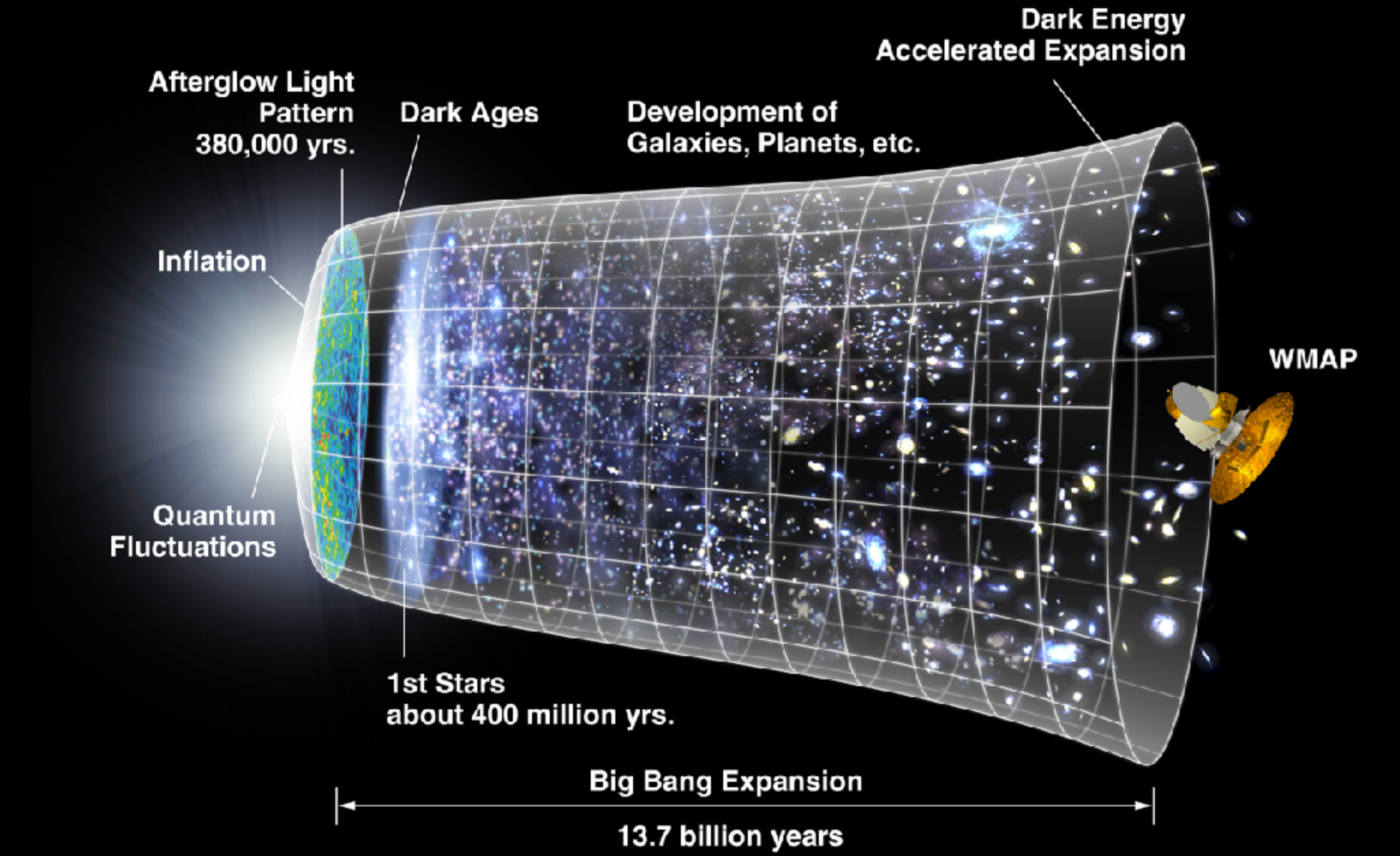
Overview

Standard Cosmology: The Lore

Hawking Radiation

Subdominant BH Population

Black Hole Domination



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

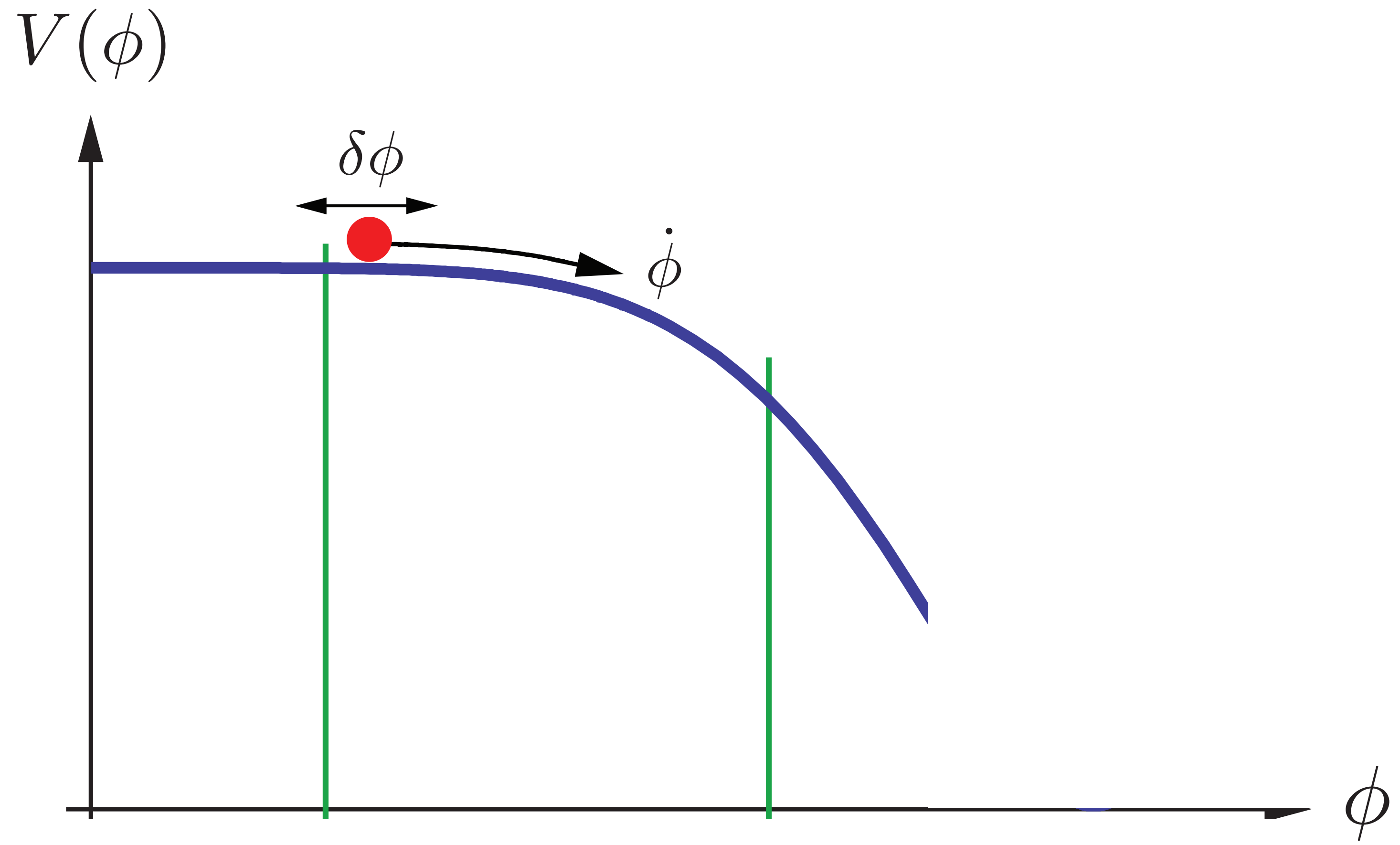
Canonical Cosmological Timeline

$t \sim 0$

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

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

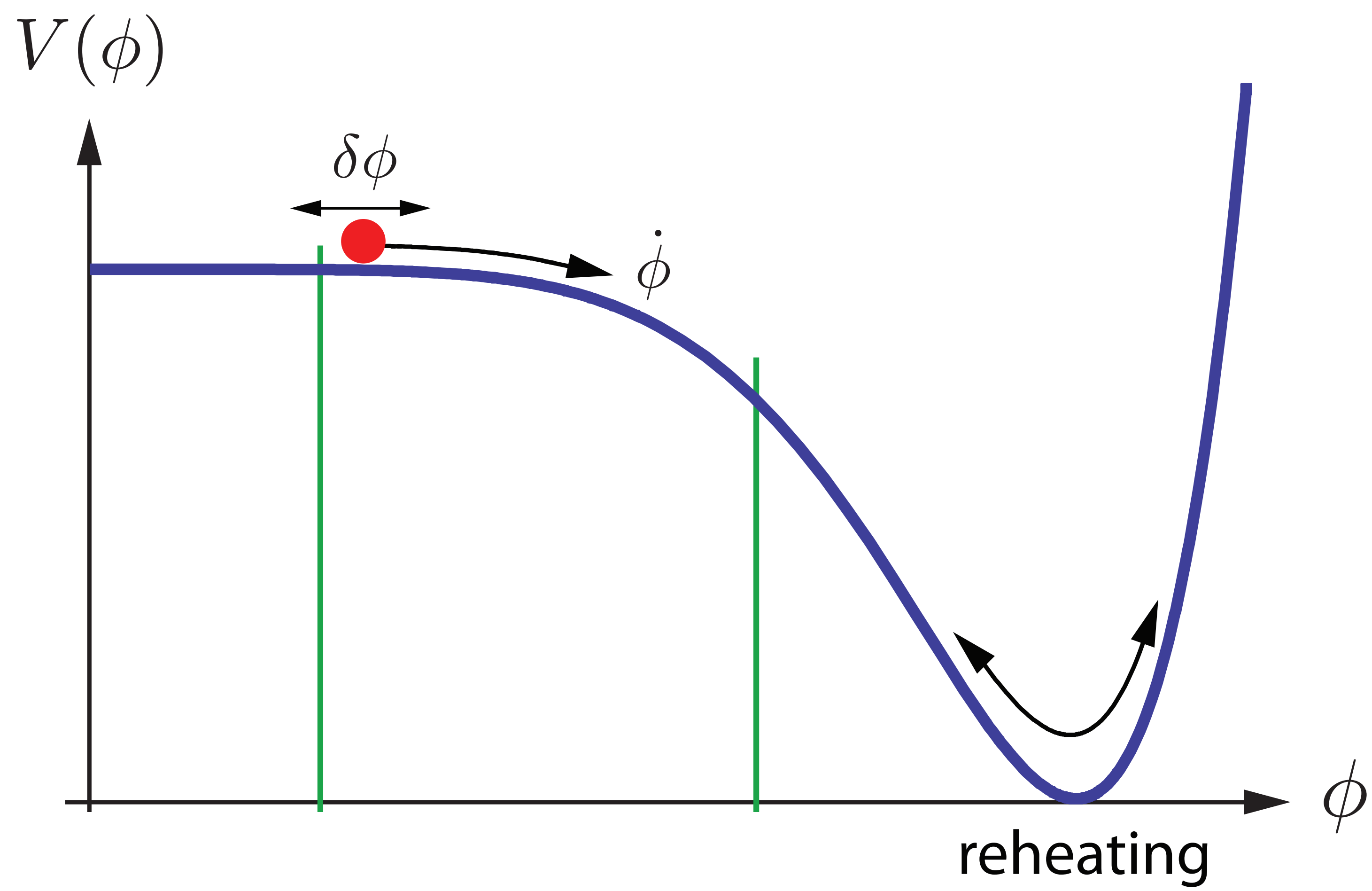
Canonical Cosmological Timeline

$t \sim 0$

Inflation

Reheating

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



$t \sim \text{sec}$

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

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

Inflation* transfers potential energy to SM radiation

Eventual radiation domination required for BBN

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

$t \sim 0$

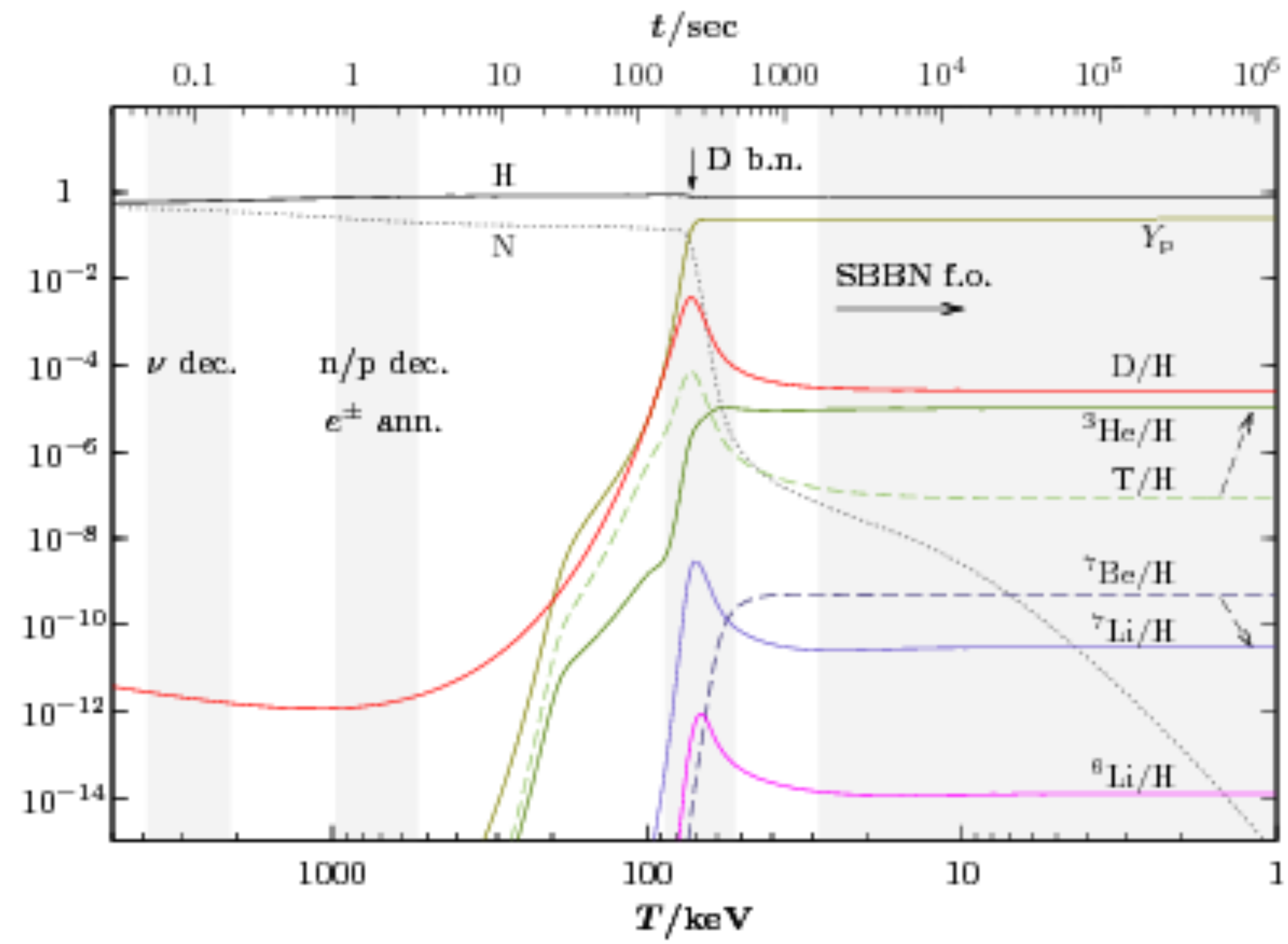
Inflation

Reheating

Baryogenesis

$t \sim \text{sec}$

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

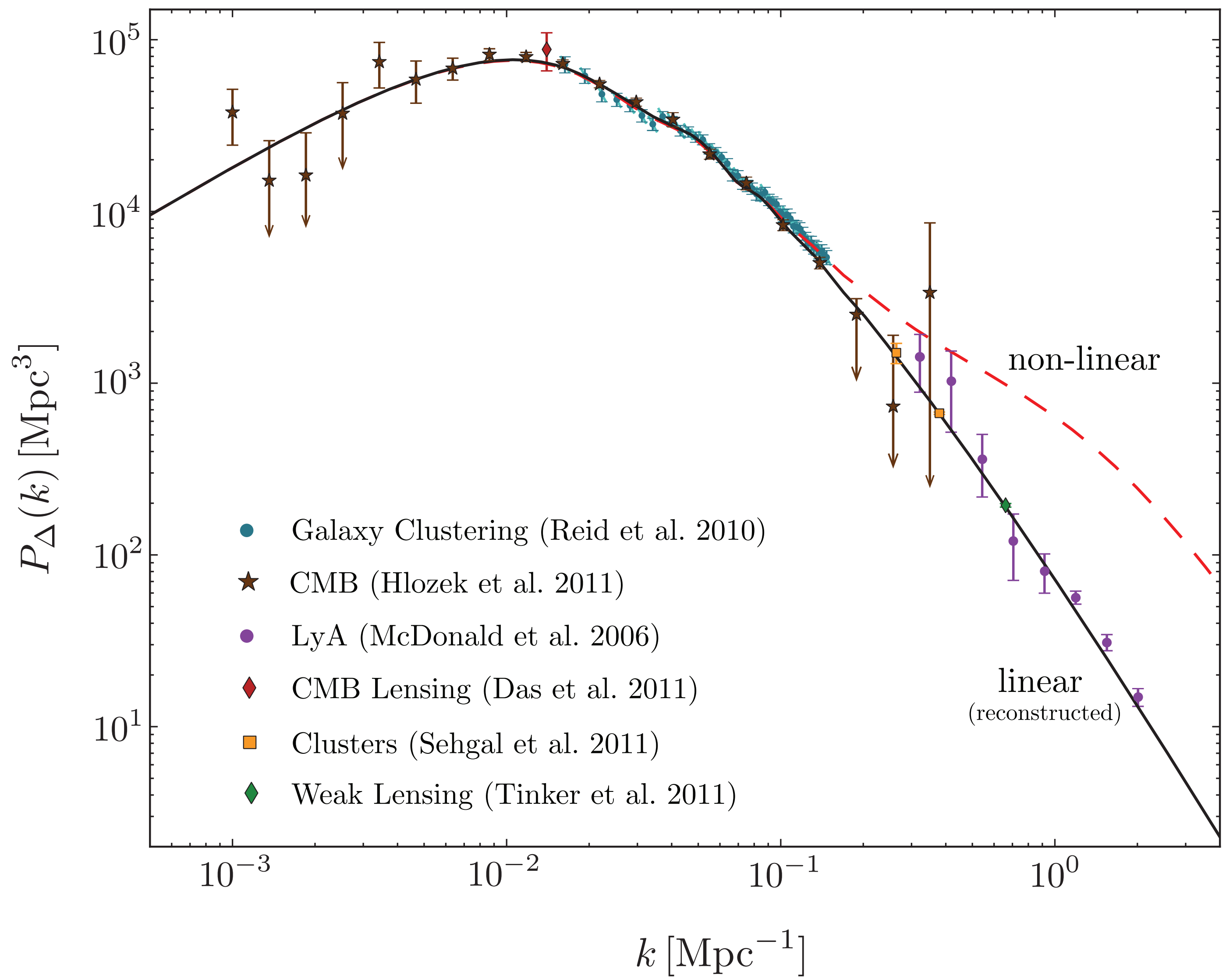
Baryogenesis

$t \sim \text{sec}$ BBN

MR Equality

$t \sim 10^5$ yr

$t \sim 13.7$ 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

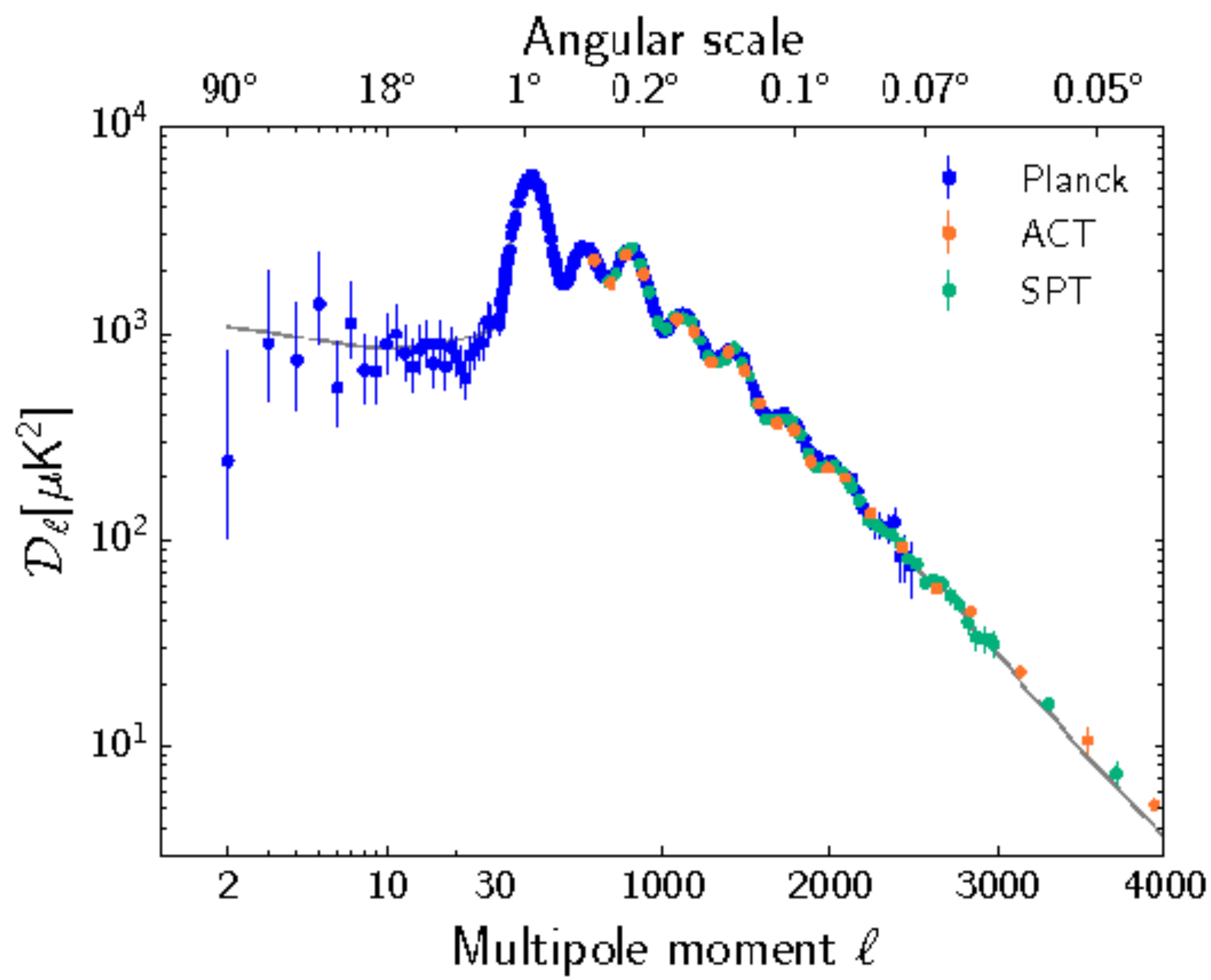
Baryogenesis

$t \sim \text{sec}$ — BBN

$t \sim 10^5$ yr — MR Equality

CMB

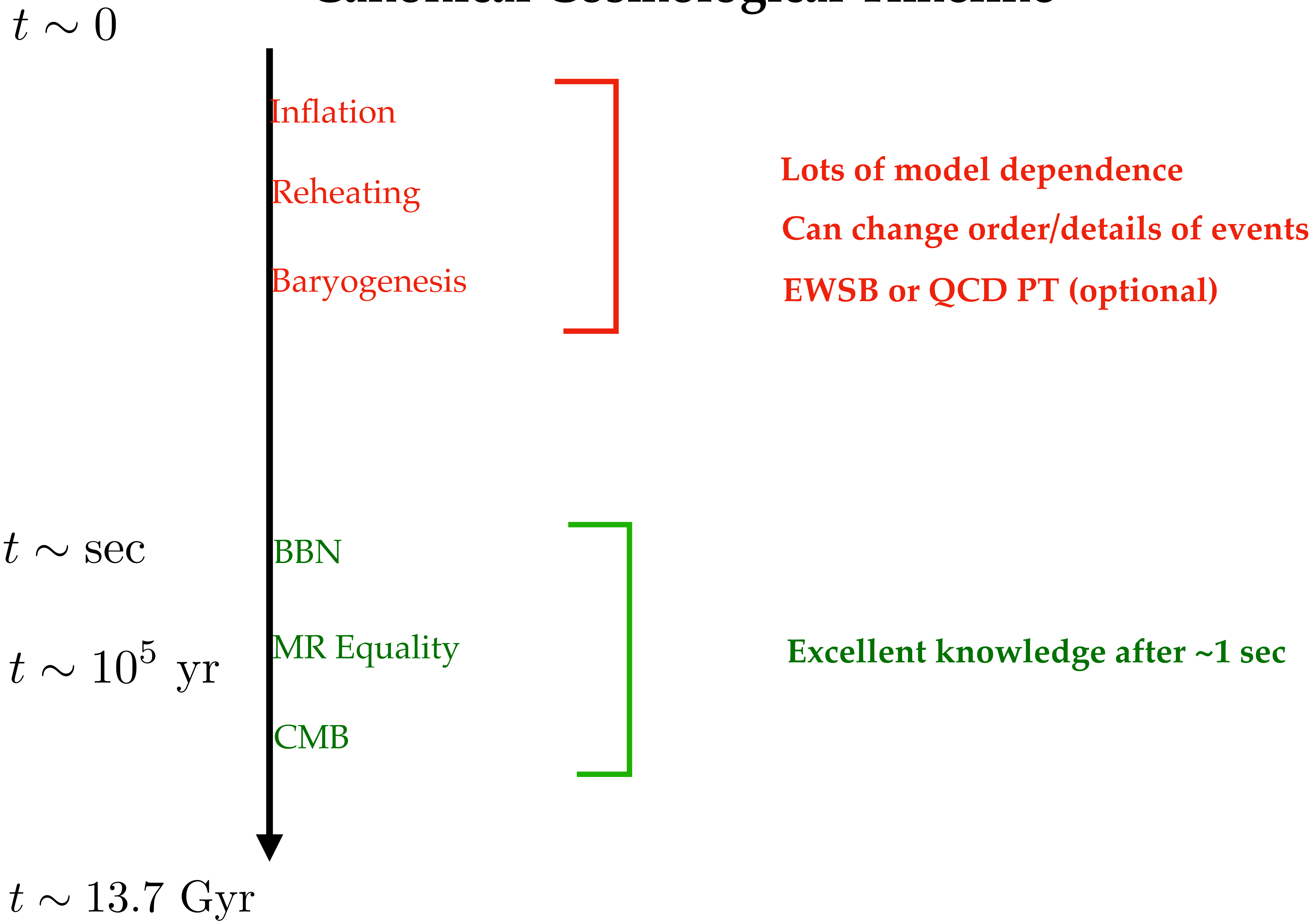
$t \sim 13.7$ Gyr



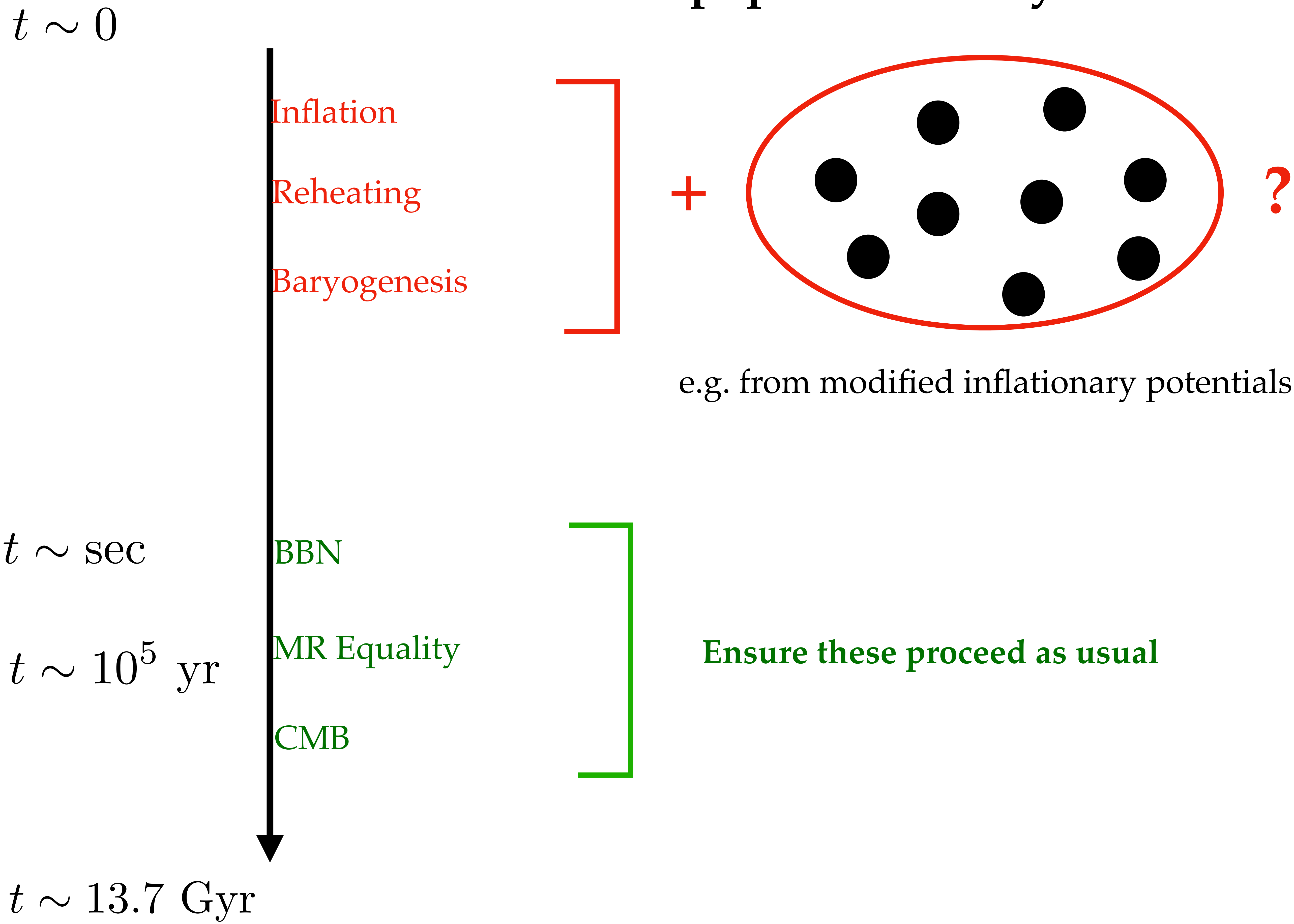
Measured CMB power spectra
Excellent agreement with data

Integrated probe of late universe physics

Canonical Cosmological Timeline



What if we add a BH population early on?



Overview

Standard Cosmology: The Lore

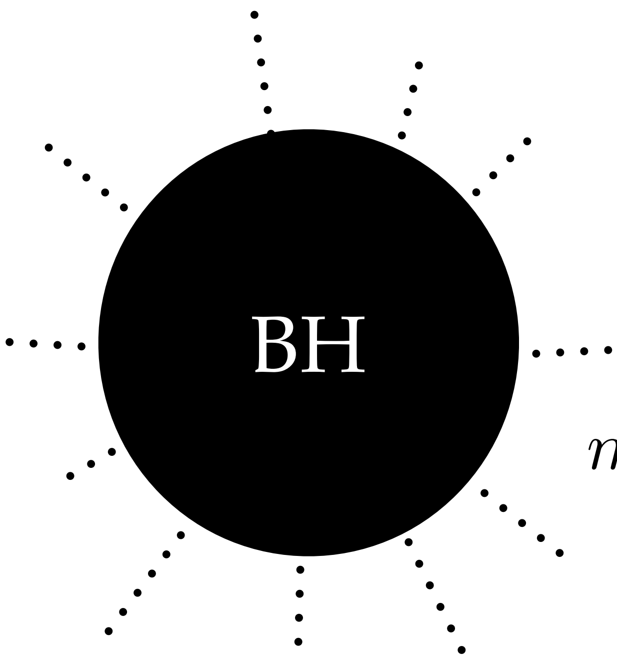
Hawking Radiation

Subdominant BH Population

Black Hole Domination

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

Hawking Radiation

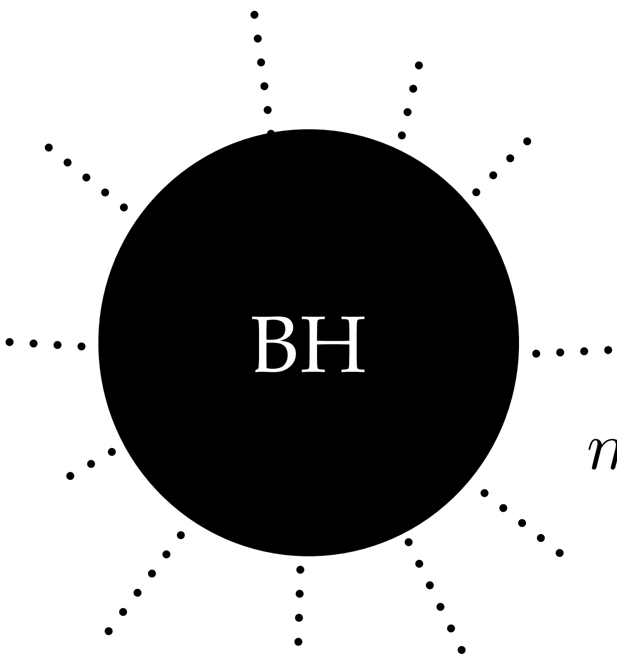


$$T_{\mathrm{BH}} = \frac{M_{\mathrm{Pl}}^2}{8\pi M_{\mathrm{BH}}} \simeq 1.05 \times 10^{13}\,\mathrm{GeV}\left(\frac{\mathrm{g}}{M_{\mathrm{BH}}}\right)$$

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

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

Hawking Radiation



i

$m_i < T_{\mathrm{BH}}$

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

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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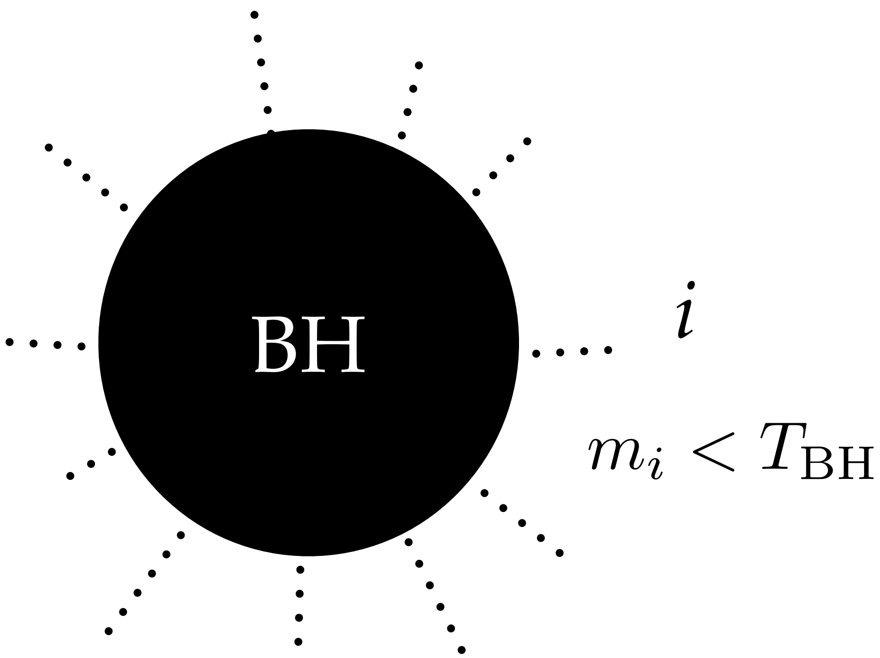
Hawking Radiation



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

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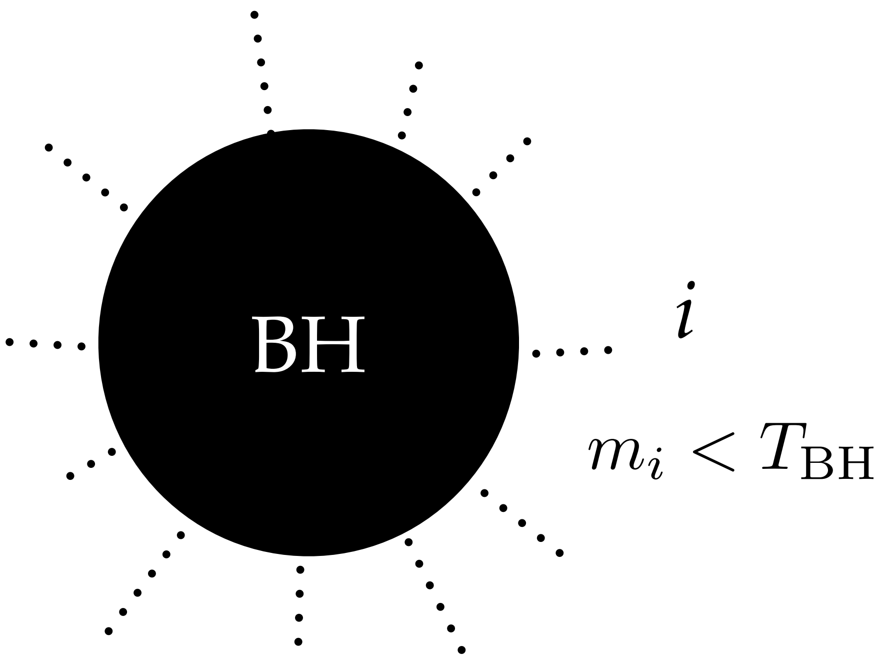
Hawking Radiation



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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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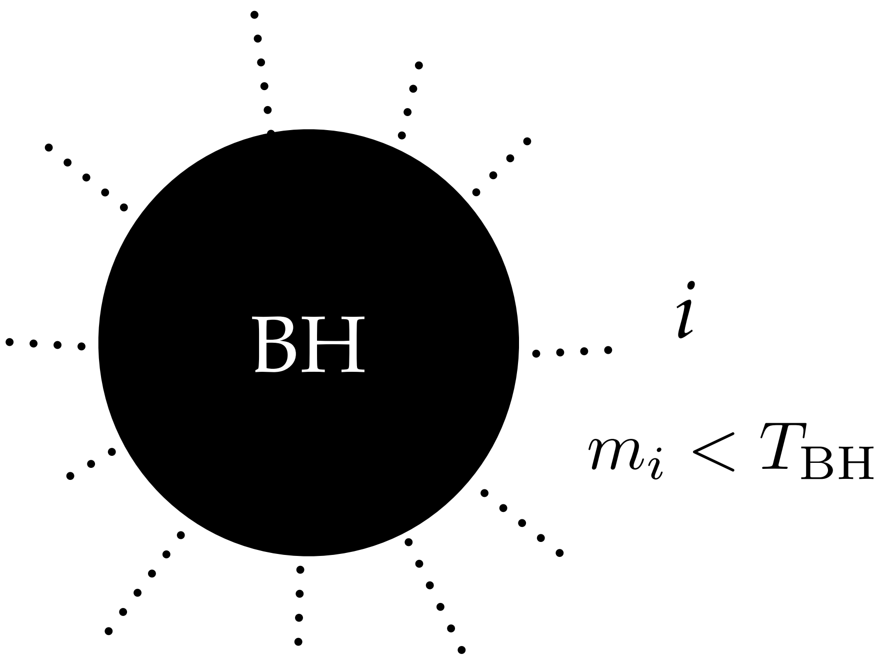
Hawking Radiation



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Unlike particle population: same evaporation time for all BH of same mass!

most particles produced near this time

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

Require full* evaporation before BBN at ~ 1 sec

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

Overview

Standard Cosmology: The Lore

Hawking Radiation

Subdominant BH Population

Black Hole Domination

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

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

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

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

Assume all BH have the same mass M_0

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

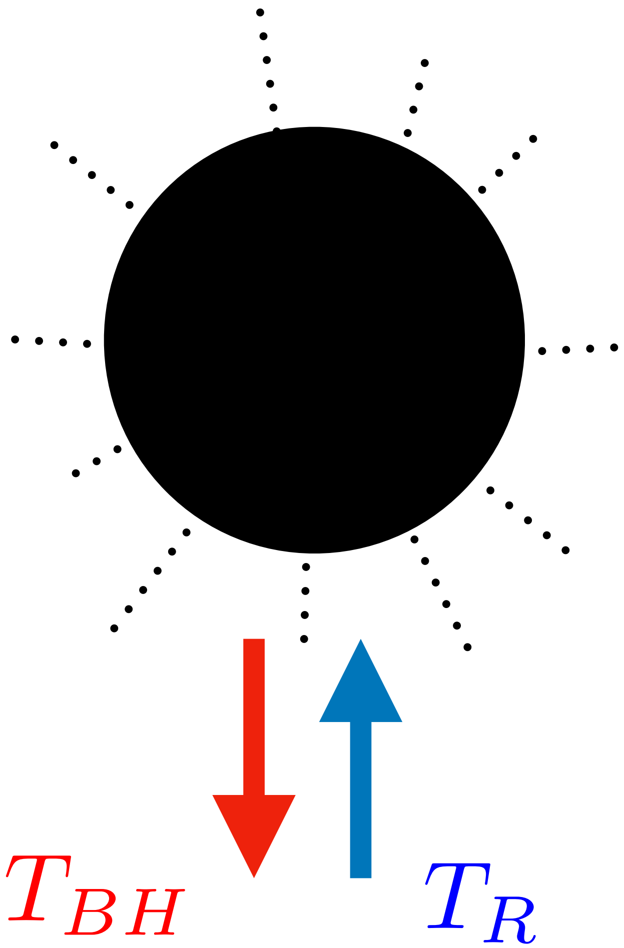
$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 \propto \rho_{\rm SM}$$

Initial BH yield at reheating

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

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

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

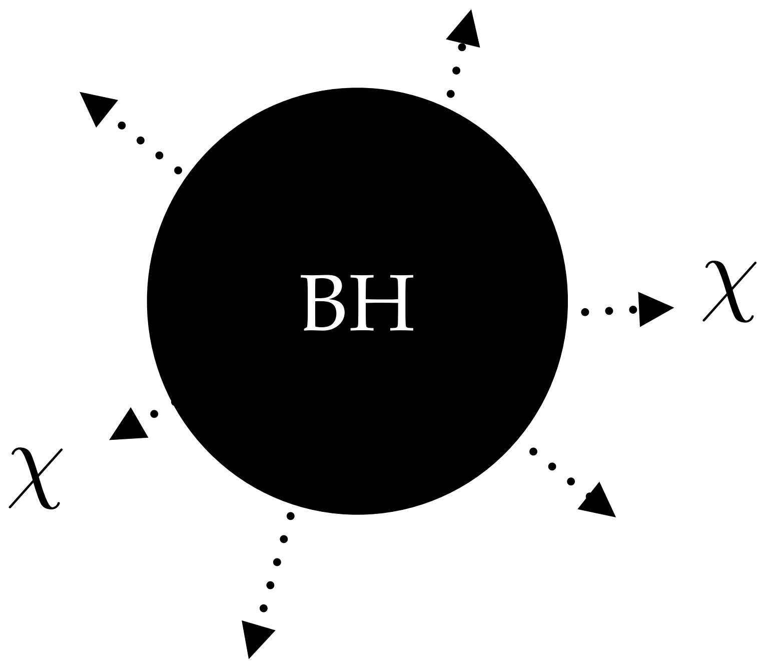
Combination of factors here satisfies

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

So accretion only matters if the radiation bath is hotter

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

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

Massive Particle Production: Dark Matter

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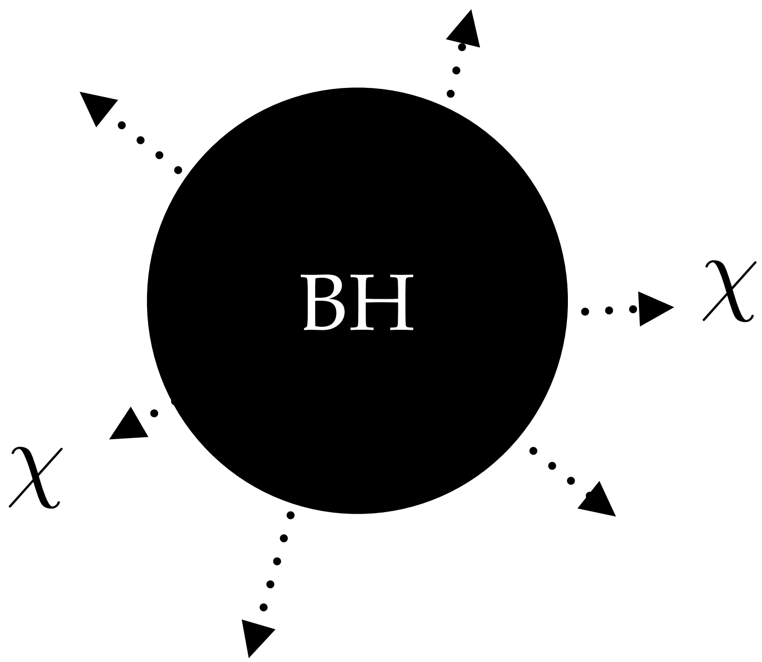

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Including "branching fraction" to DM particles

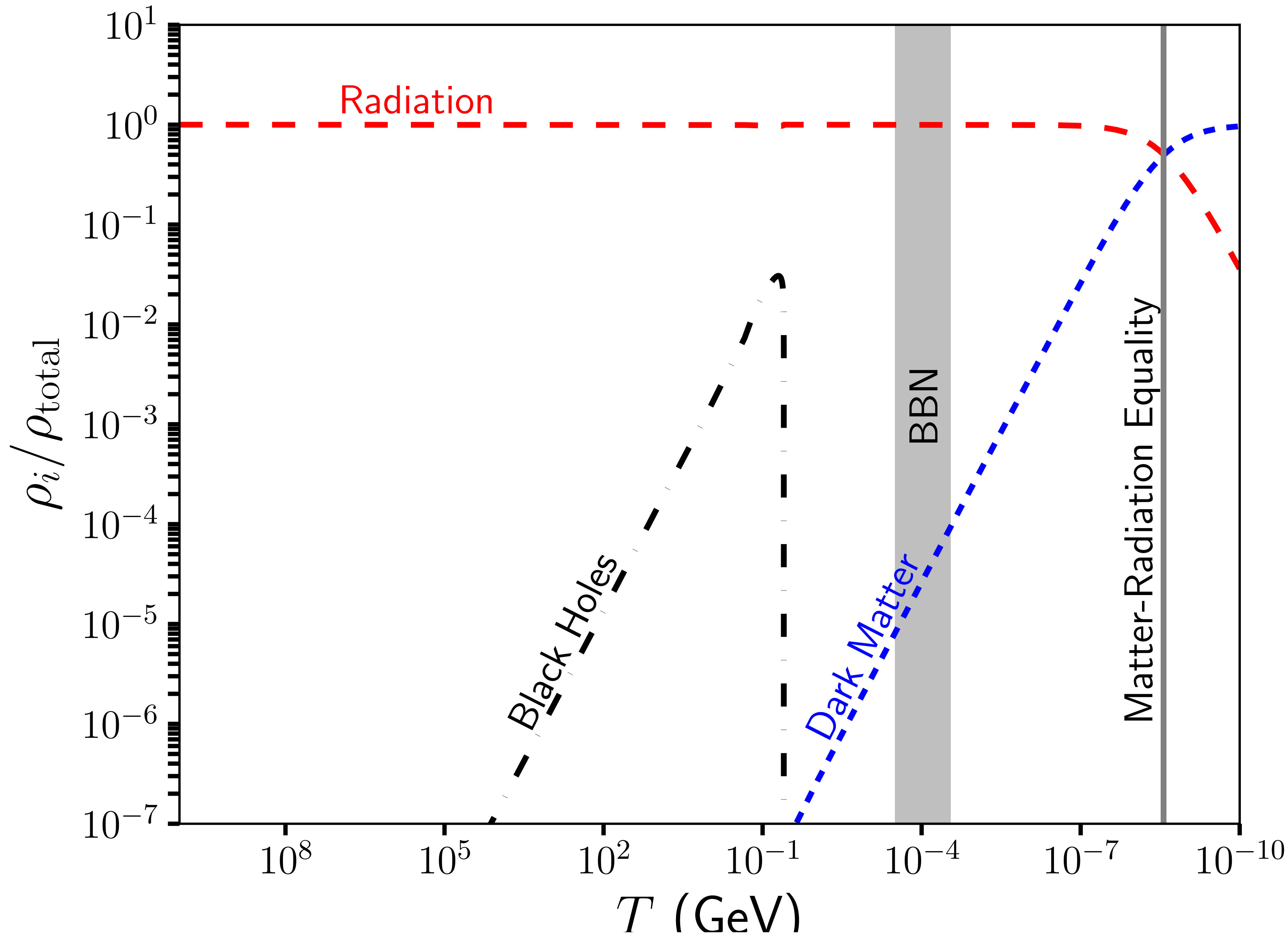
$$dN_\chi = \frac{g_\chi}{g_\star + g_\chi} dN \implies N_\chi = \int_{T_0}^{\infty} dN_\chi = \frac{M_{\rm Pl}^2}{24\pi}\int_{m_\chi}^{\infty}\frac{dT_{\rm BH}}{T_{\rm BH}^3}\frac{g_\chi}{g_\star(T_{\rm BH}) + g_\chi}$$

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

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

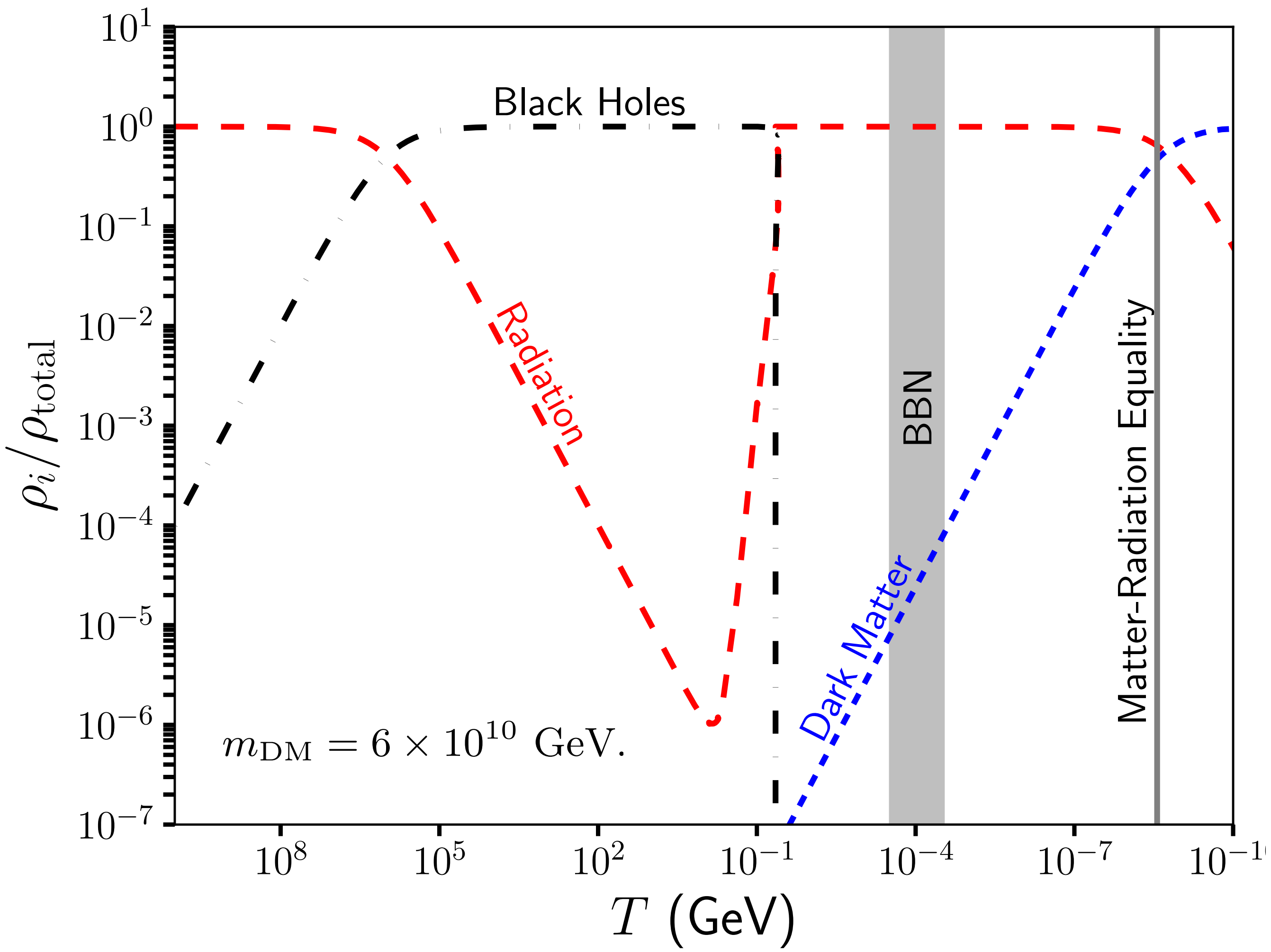
$$\rho_{\mathrm{BH}}(\tau) \propto M_{\mathrm{Pl}}^2 H^2(\tau) = \frac{4M_{\mathrm{Pl}}^2}{9\tau^2} = \frac{\pi^2 g_*}{30} T_{\mathrm{RH}}^4$$

Now insensitive to initial fraction or temperature

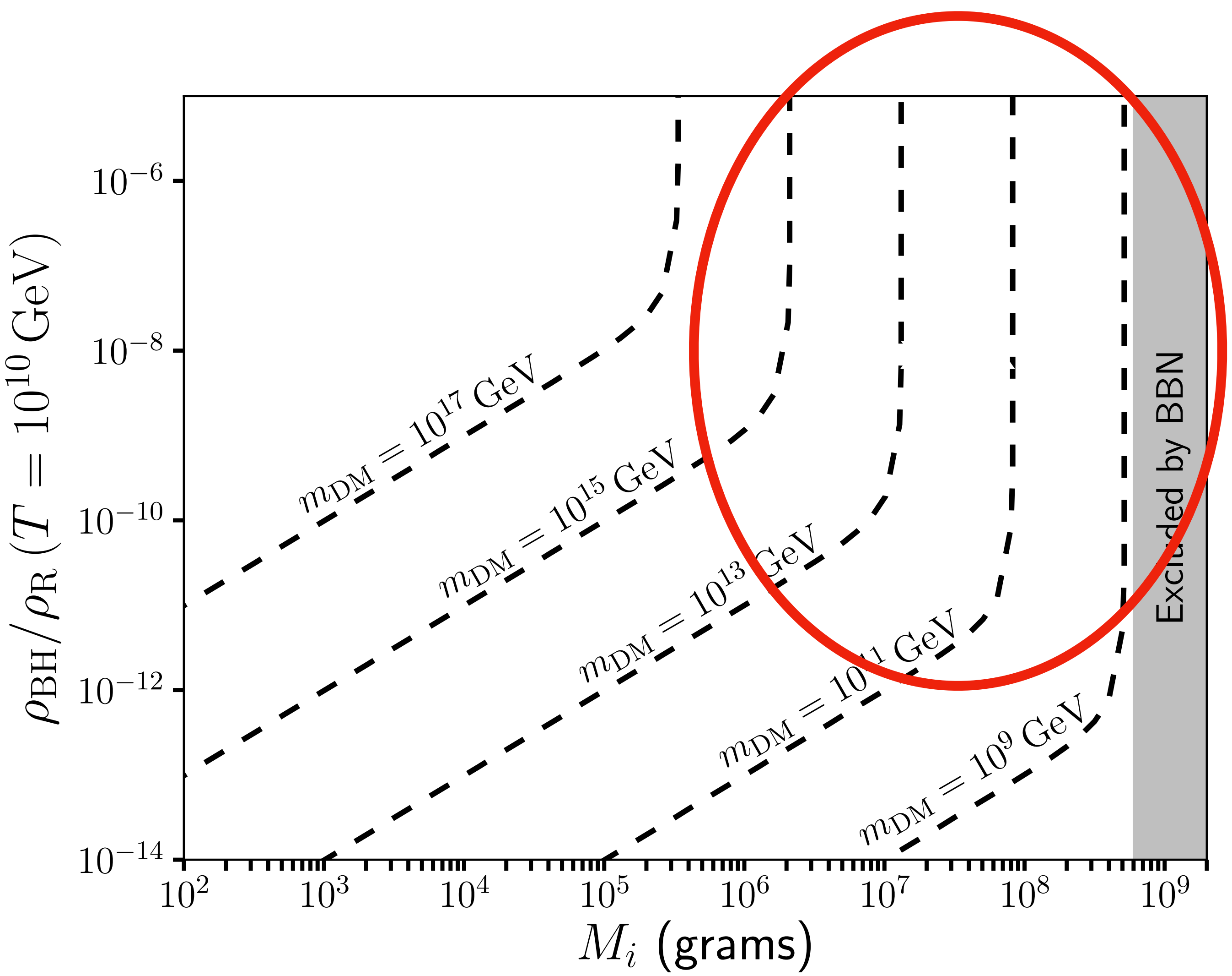
$$T_{\mathrm{RH}} \simeq 50\,\mathrm{MeV}\left(\frac{10^8\,\mathrm{g}}{M_i}\right)^{3/2}\left(\frac{g_{\star,H}(T_{\mathrm{BH}})}{108}\right)^{1/2}\left(\frac{14}{g_\star(T_{\mathrm{RH}})}\right)^{1/4}.$$

"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: $m_{\rm DM} > 10^9\,{\rm GeV}$

Overview

Standard Cosmology: The Lore

Hawking Radiation

Subdominant BH Population

Black Hole Domination

Black Hole Domination

Inflation

↓ Anything

BH population

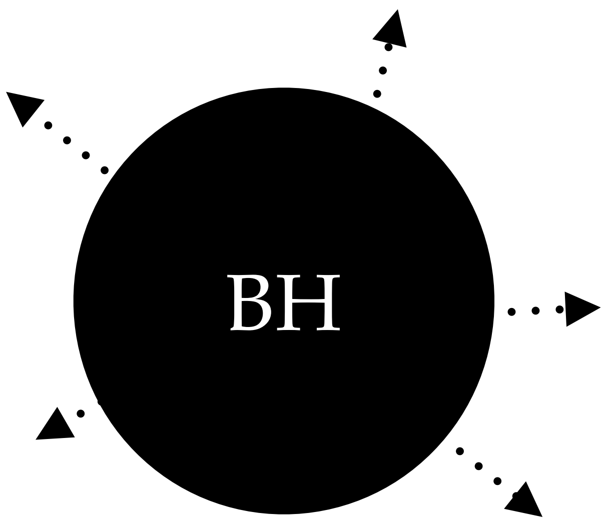
↓ Hawking Evaporation

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

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

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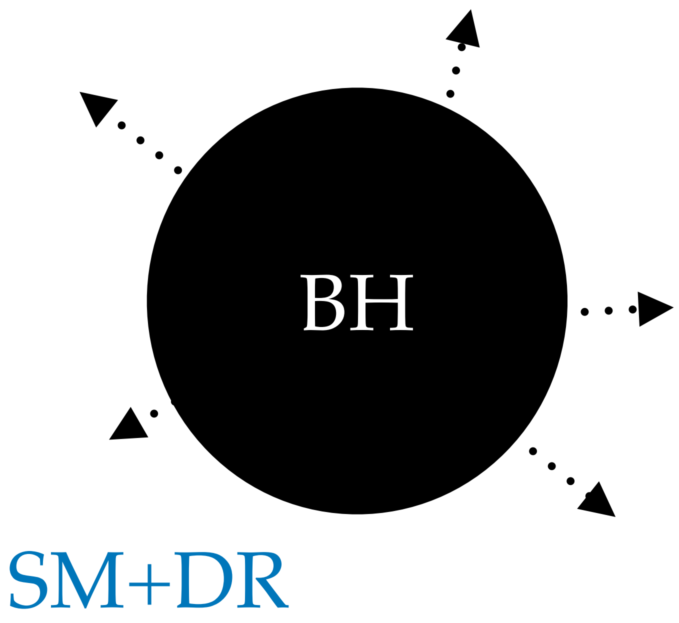

$$\Delta N_{\rm eff} \propto \frac{\rho_{\rm DR}(T_{\rm EQ})}{\rho_{\rm SM}(T_{\rm EQ})}$$

System evolves according to

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

BH population depletion

Depends only on BH mass and assumption of BH domination

Dark Radiation from pBH Domination

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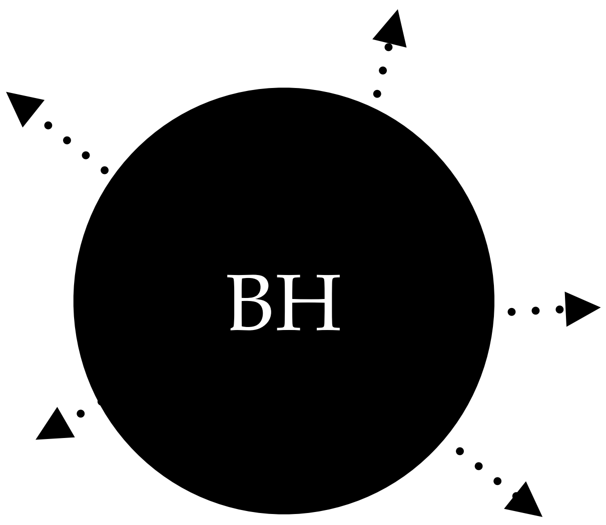

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$$\frac{d\rho_{\rm SM}}{dt} = -4\rho_{\rm SM} - \rho_{\rm BH} \frac{dM_{\rm BH}}{dt}\bigg|_{\rm SM}\frac{1}{M_{\rm BH}}$$

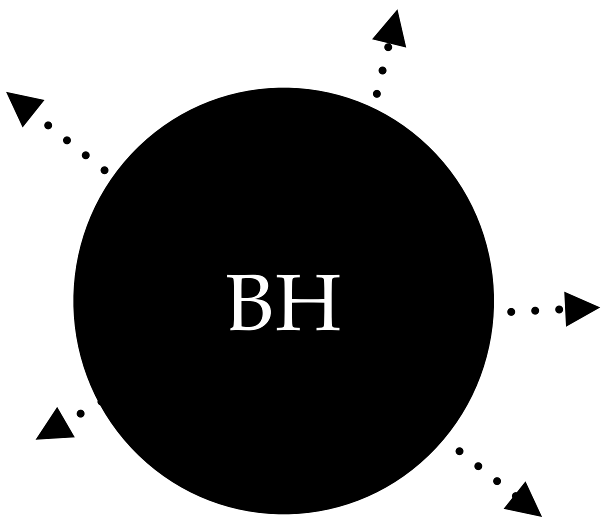
SM radiation density sets RH temp

Only produce species with mass less than BH temp

Integrable

Dark Radiation from pBH Domination

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



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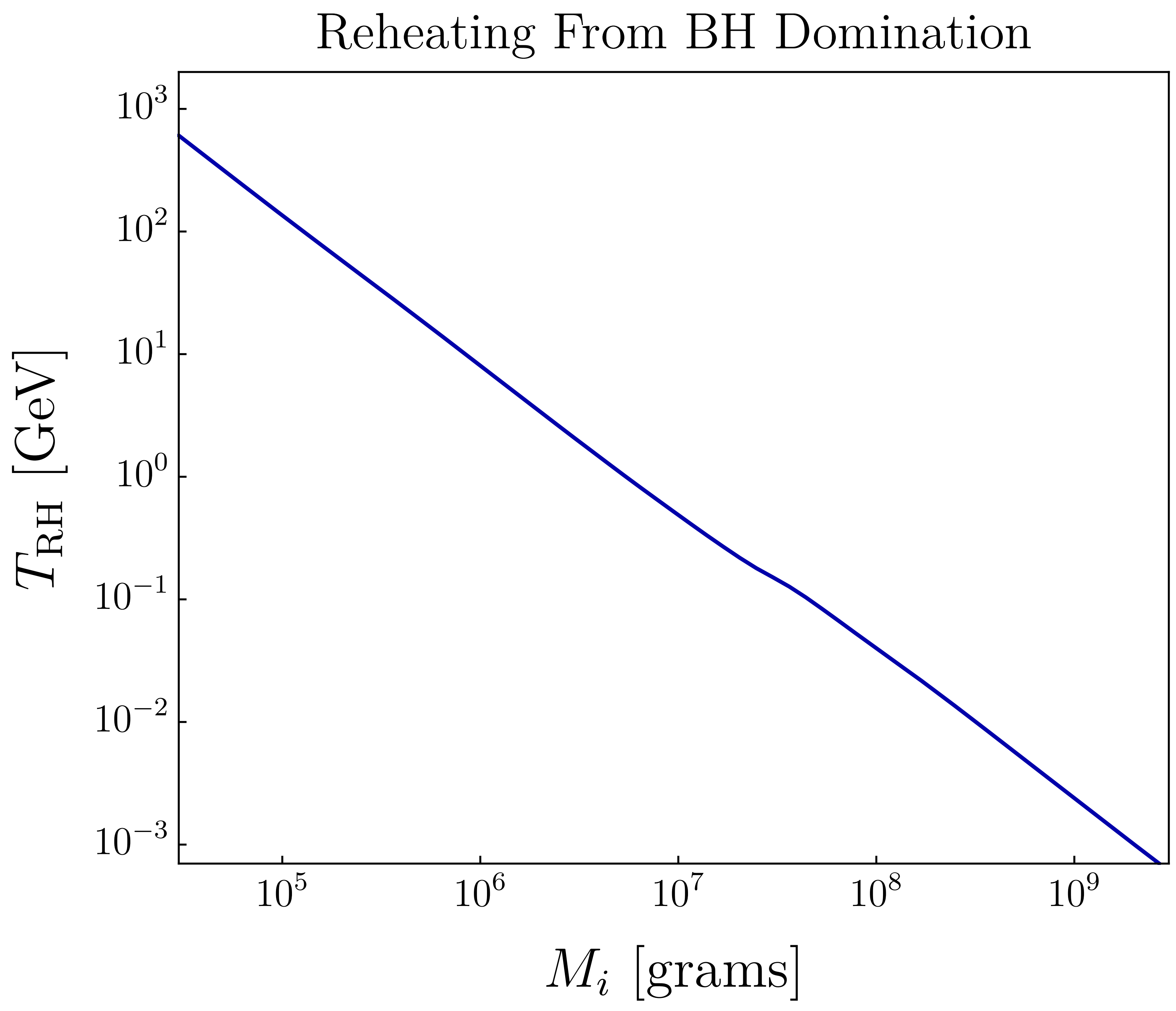
$$\frac{d\rho_{\rm SM}}{dt} = -4\rho_{\rm SM} - \rho_{\rm BH}\frac{dM_{\rm BH}}{dt}\bigg|_{\rm SM}\frac{1}{M_{\rm BH}}$$

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

DR density, also 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

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

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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Ratio to SM set by Hawking DOF

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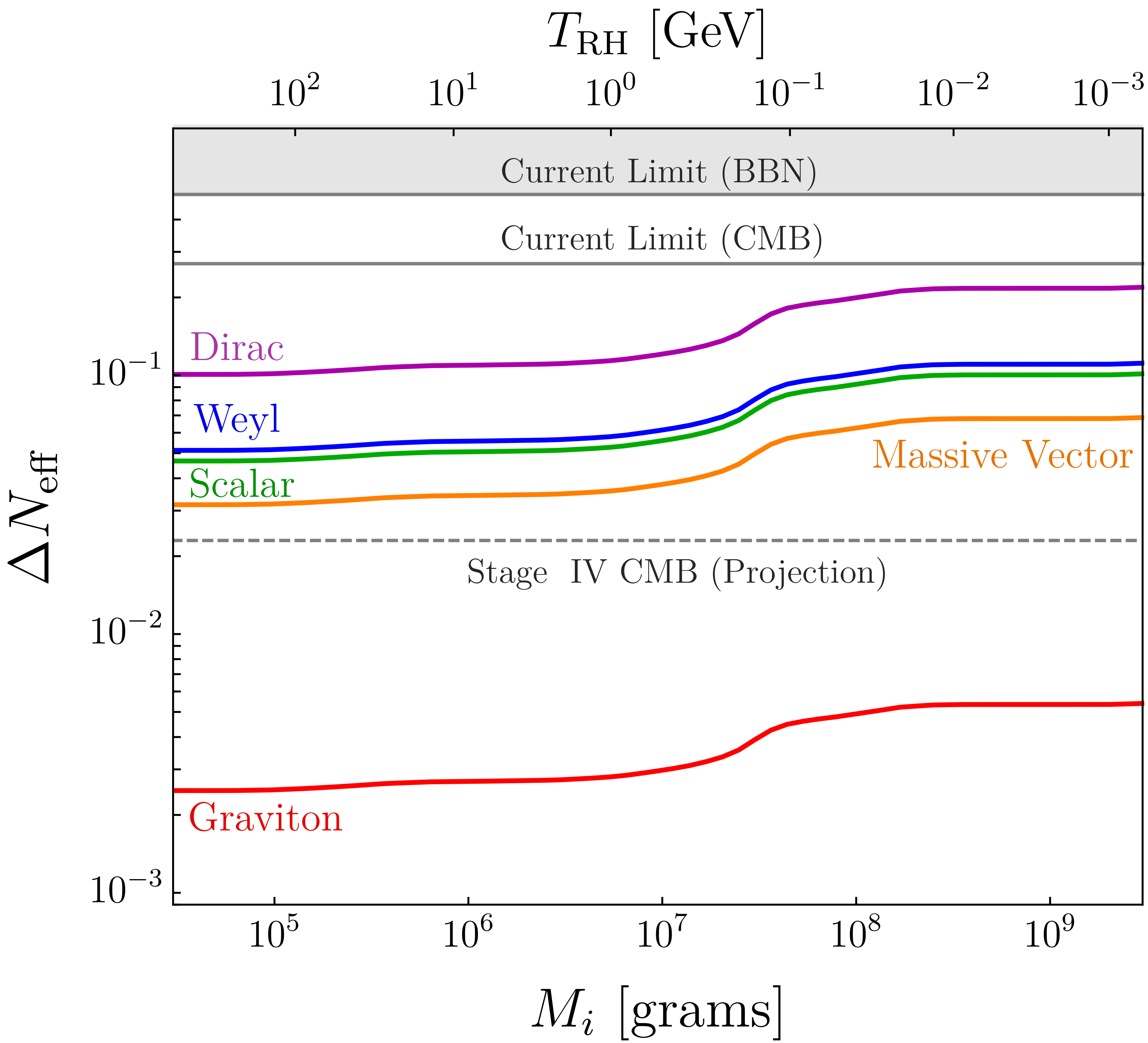
Final result *milder* than naive expectation

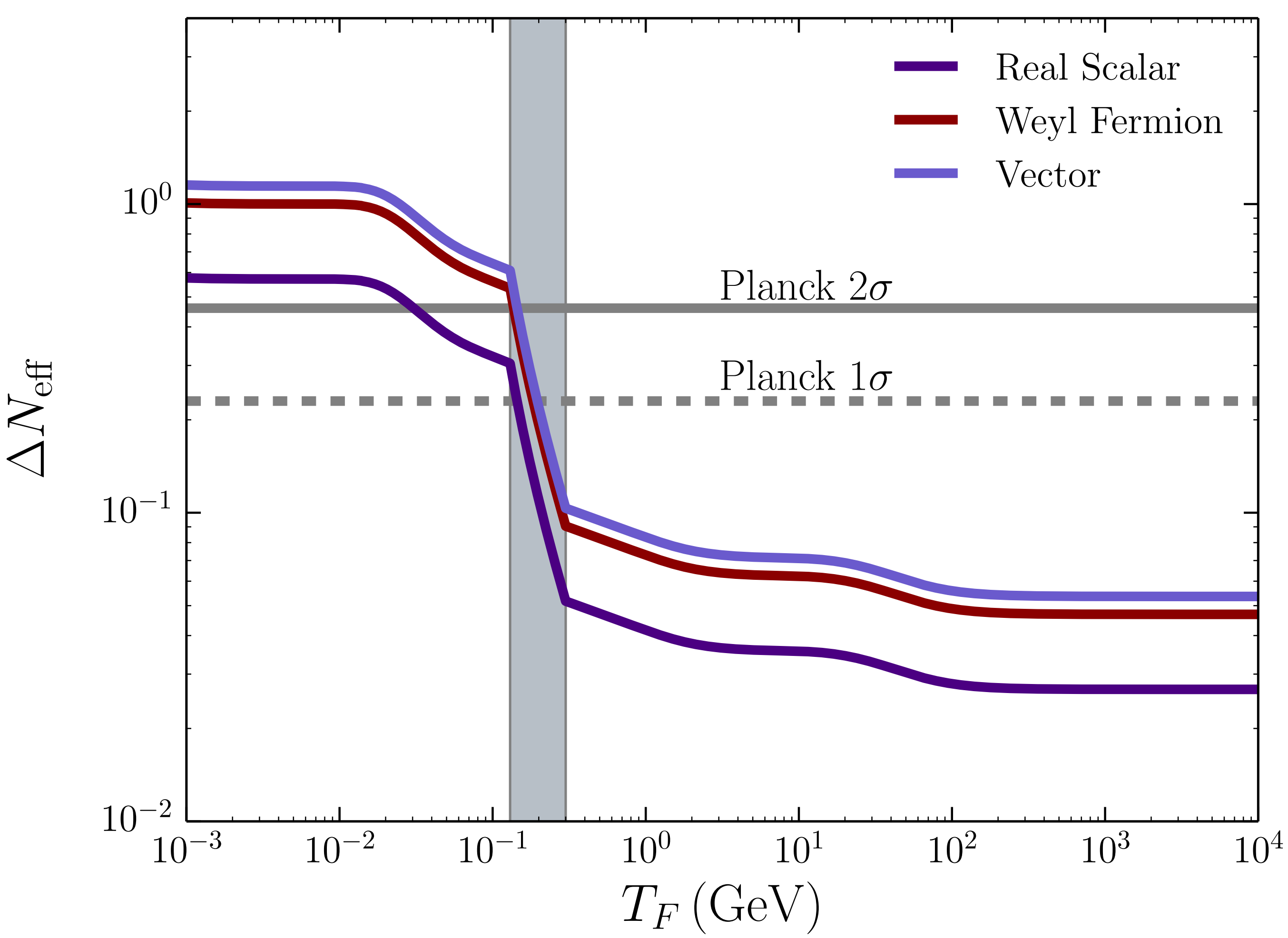
$$\Delta N_{\rm eff} = \frac{\rho_{\rm DR}(T_{\rm EQ})}{\rho_R(T_{\rm EQ})}\left[N_\nu + \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\right] \approx 0.10\left(\frac{g_{{\rm DR},H}}{4}\right)\left(\frac{106}{g_\star(T_{\rm RH})}\right)^{1/3}$$

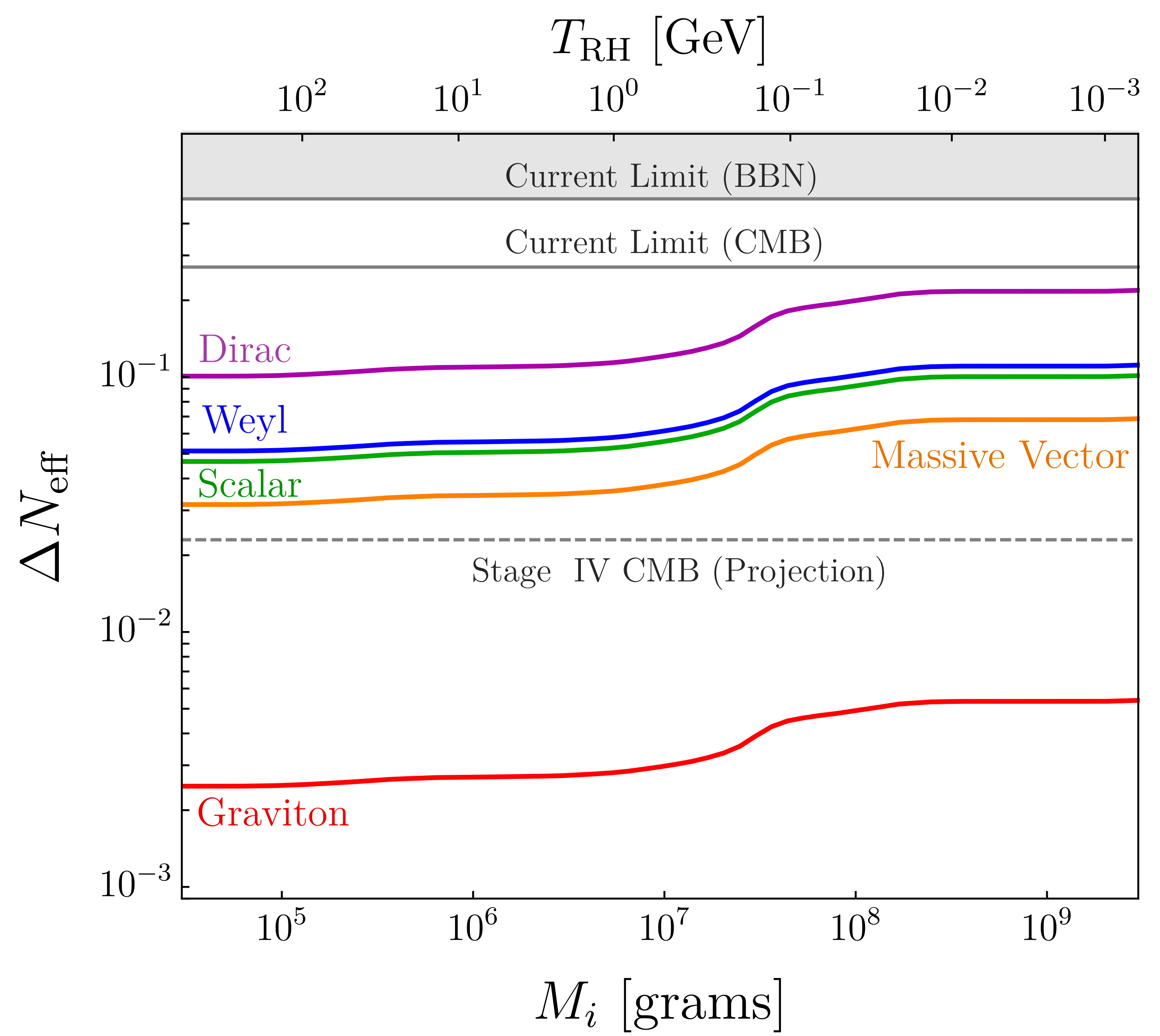
BH is hotter than RH temp —> smaller branching to DS

Neff in BH Domination



Comparing to Conventional Thermal Relics

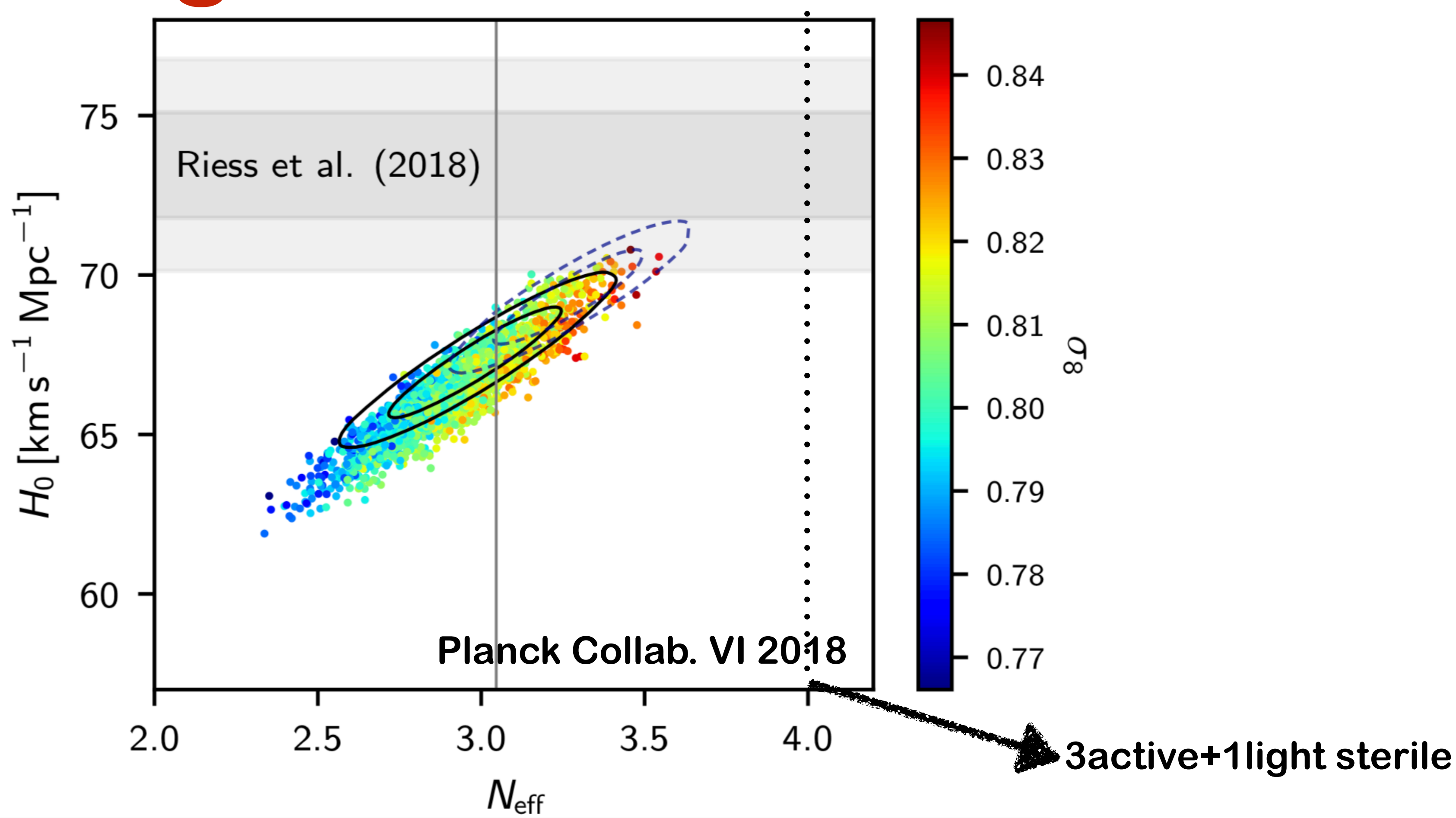




Flaugher et. al. CMBS4 science book

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

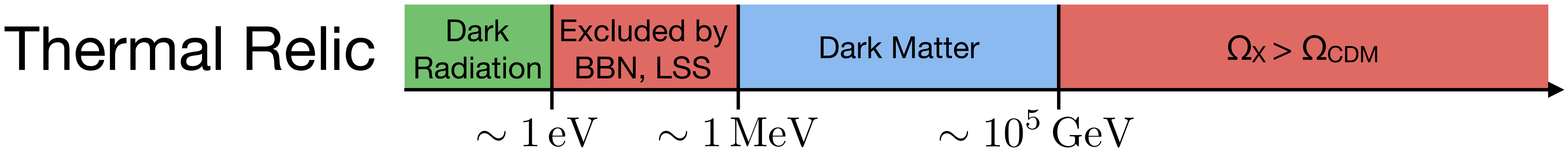
Relieving the tension with Neff



$$\frac{r_*}{3000\,\mathrm{Mpc}} = \int_{z_*}^{\infty} \frac{c_s dz}{\left[\Omega_\gamma h^2 \left(1+\frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}} N_{\rm eff}\right)(1+z)^4 + \Omega_m h^2 (1+z)^3\right]^{1/2}}$$

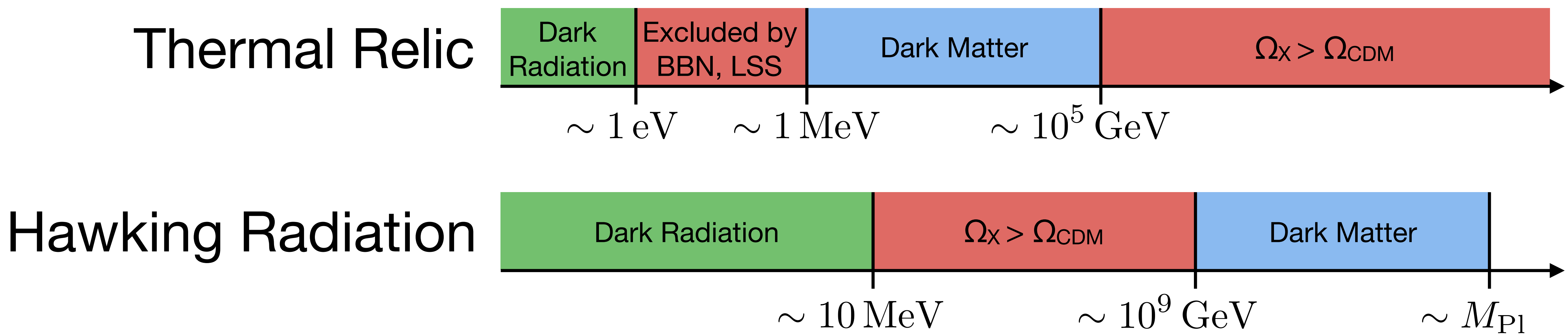
$$\frac{d_A}{3000\,\mathrm{Mpc}} = \int_0^{z_*} \frac{dz}{\left[\Omega_m h^2 (1+z)^3 + \Omega_\Lambda h^2\right]^{1/2}}$$

Comparing to Conventional Thermal Relics



Usual picture of particles in thermal equilibrium

Comparing to Conventional 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]

Concluding Remarks

-We don’t know what happened before BBN

-Early BH population: evaporation can seed initial conditions for BBN

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

-Interesting Neff range to *reduce* Hubble tension

Other possibilities:

Modified structure formation (Ericeck 2015)?

Vary distribution of BH masses?

Add BH spins or charges?