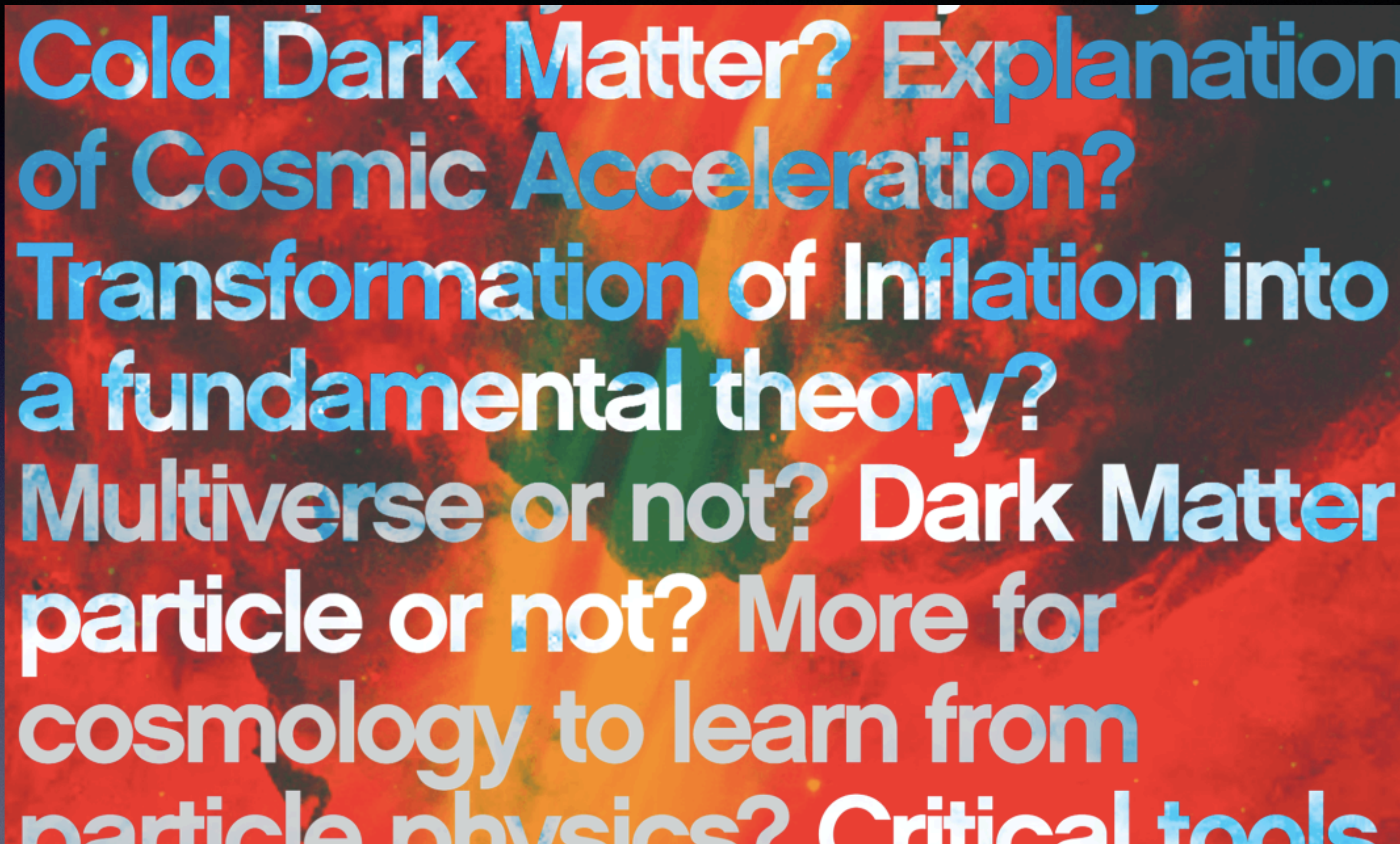
Dark Radiation & Superheavy Dark Matter from Black Hole Domination

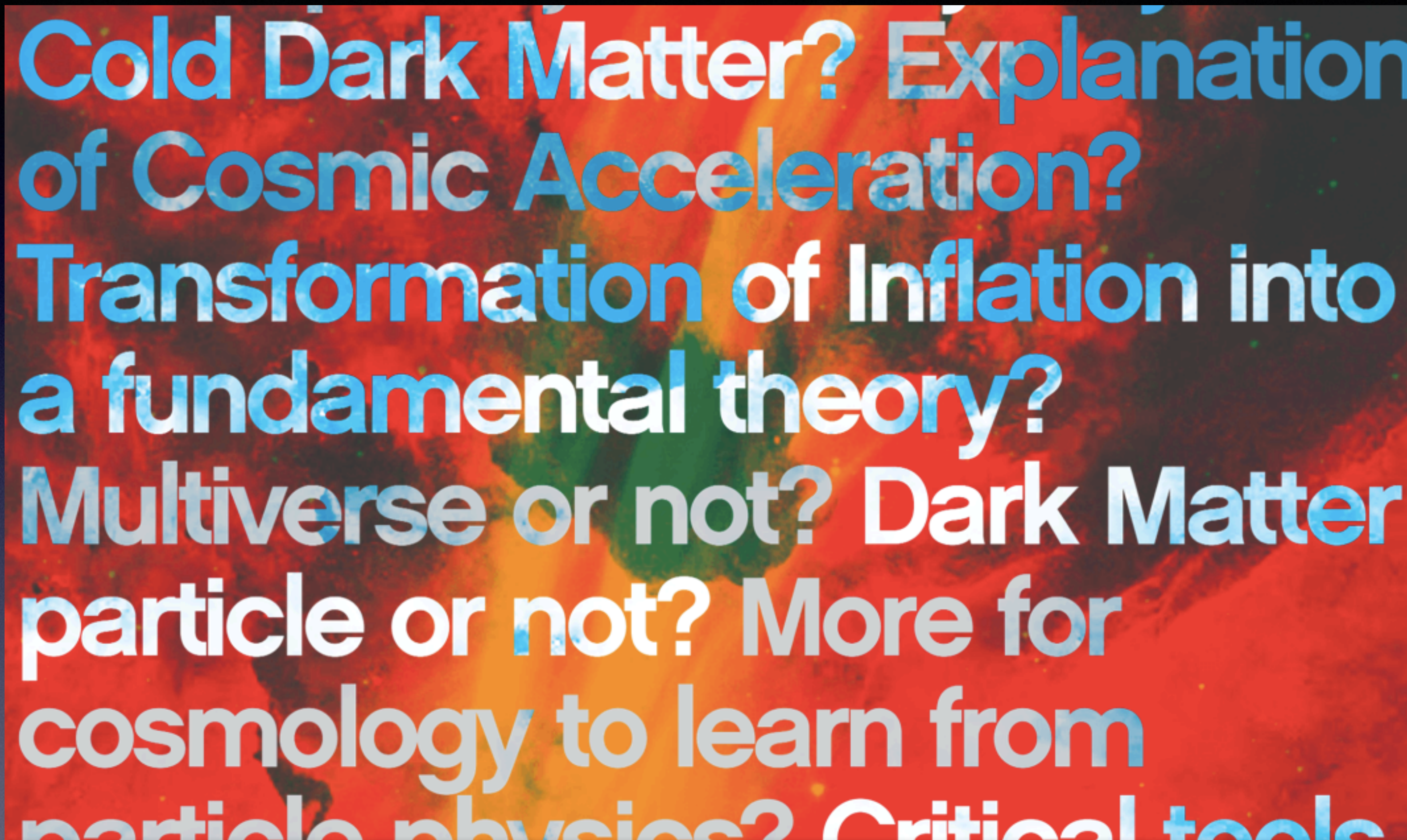
Sam McDermott

Cosmic Controversies, Oct 7 2019

1905.01301 (with Dan Hooper and Gordan Krnjaic)
(+ongoing…)

Fermilab

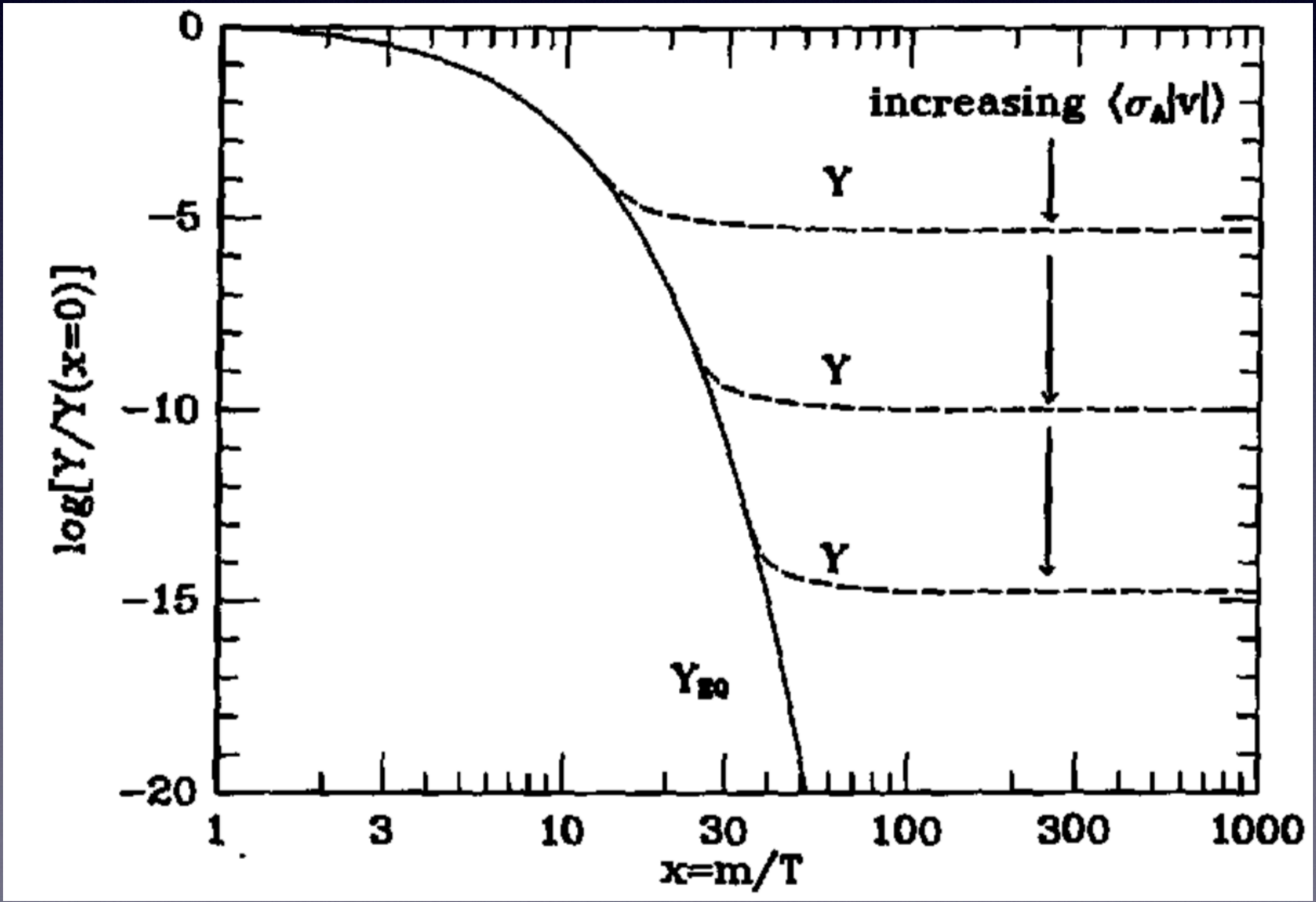

Cold Dark Matter? Explanation
of Cosmic Acceleration?
Transformation of Inflation into
a fundamental theory?
Multiverse or not? Dark Matter
particle or not? More for
cosmology to learn from
particle physics? Critical tools



Thermal relic or not?

The Origin of (Particle) Species

Thermal Relic



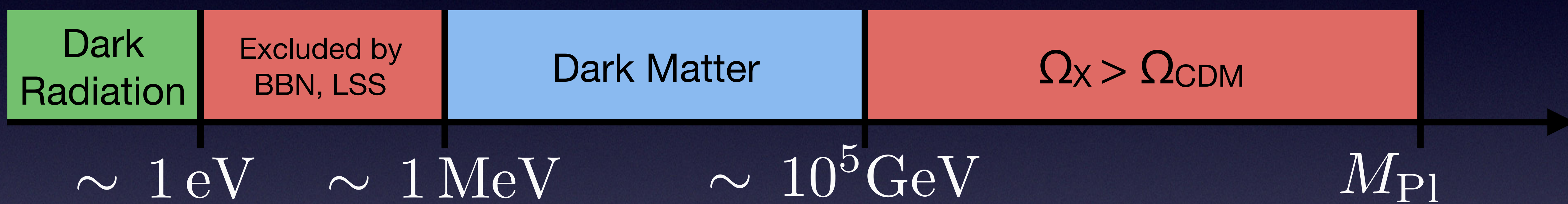
The Early Universe
Kolb & Turner

The Origin of (Particle) Species

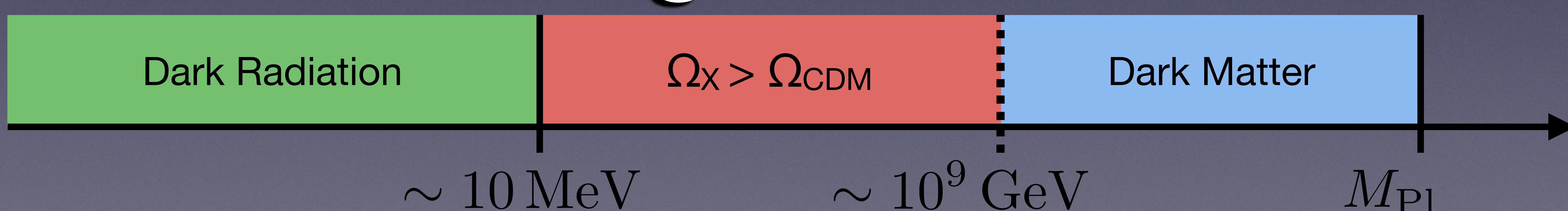
Thermal Relic

The Origin of (Particle) Species

Thermal Relic



Hawking Radiation

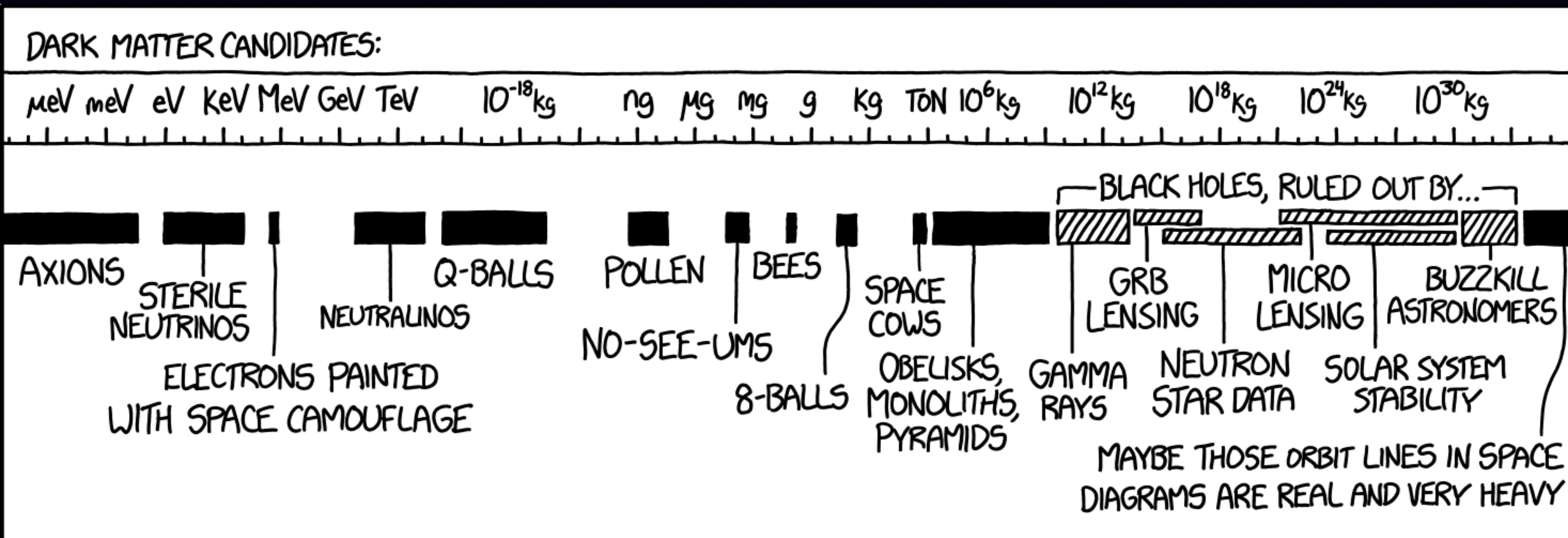


Outline

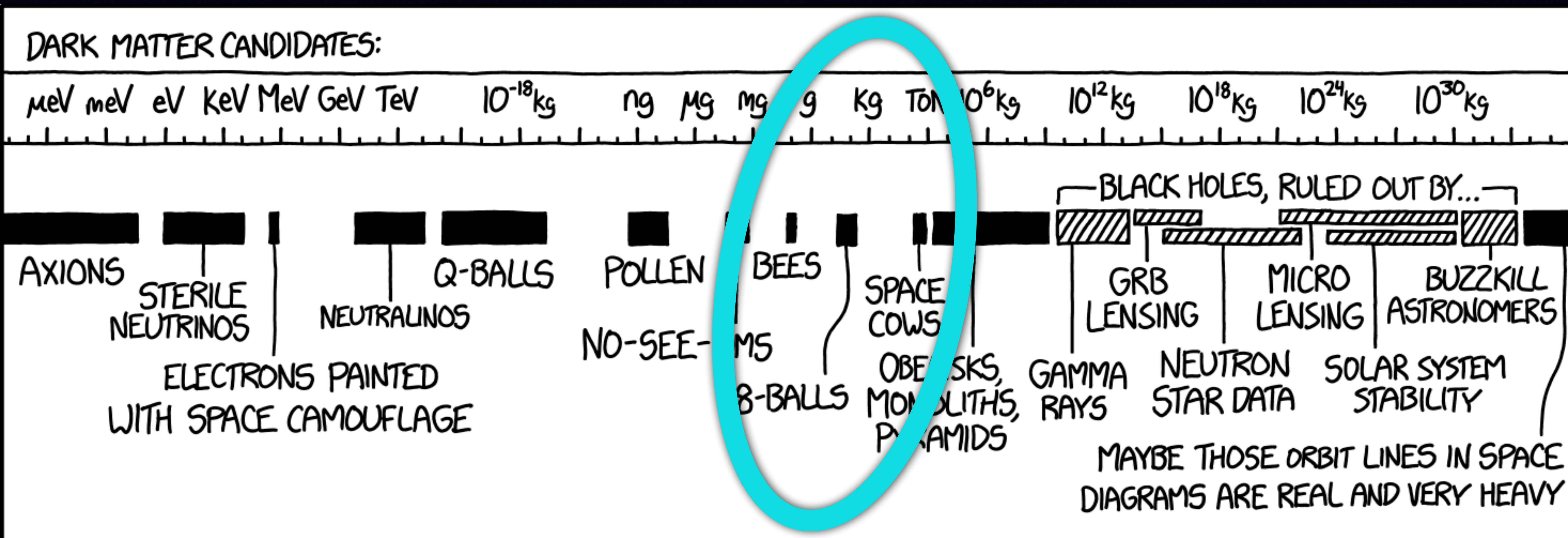
1. The Mass Range of Primordial Black Holes
2. Dark Radiation
3. Superheavy Dark Matter
4. Concluding Comments

Outline

1. The Mass Range of Primordial Black Holes
2. Dark Radiation
3. Superheavy Dark Matter
4. Concluding Comments



https://xkcd.com/2035/



https://xkcd.com/2035/

Black Hole Temperature

- Every black hole emits like a blackbody at a temperature (Bekenstein 1973; Hawking 1974):

$$T_{\rm BH} = \frac{M_{\rm Pl}^2}{8\pi M_{\rm BH}}$$

Black Hole Temperature

- Every black hole emits like a blackbody at a temperature (Bekenstein 1973; Hawking 1974):

$$T_{\mathrm{BH}} = \frac{M_{\mathrm{Pl}}^2}{8\pi M_{\mathrm{BH}}}$$

- For $M_{BH} \sim M_\odot$, $T_{BH} \sim 10^{-20}$ GeV

Black Hole Temperature

- Every black hole emits like a blackbody at a temperature (Bekenstein 1973; Hawking 1974):

$$T_{\rm BH} = \frac{M_{\rm Pl}^2}{8\pi M_{\rm BH}}$$

- For $M_{BH} \sim M_{\odot}$, $T_{BH} \sim 10^{-20}$ GeV
- For $M_{BH} \sim 10^8$ gram, $T_{BH} \gg$ TeV

Black Hole Evaporation

- Evaporation rate formula (Hawking 1974):

$$\frac{dM_{\rm BH}}{dt} = -\frac{\mathcal{G}\, g_{\star,H}(T_{\rm BH})\, M_{\rm Pl}^4}{30720\,\pi\, M_{\rm BH}^2}$$

$$\simeq -7.6\times 10^{24}\,{\rm g\,s^{-1}}\;\, g_{\star,H}(T_{\rm BH})\left(\frac{\rm g}{M_{\rm BH}}\right)^2$$

Black Hole Evaporation

- Evaporation rate formula (Hawking 1974):

$$\frac{dM_{\rm BH}}{dt} = -\frac{\mathcal{G}\, g_{\star,H}(T_{\rm BH})\, M_{\rm Pl}^4}{30720\,\pi\, M_{\rm BH}^2}$$

$$\simeq -7.6 \times 10^{24}\,{\rm g\,s^{-1}}\; g_{\star,H}(T_{\rm BH}) \left(\frac{\rm g}{M_{\rm BH}}\right)^2$$

- For $g_{\star,H}$ constant with M_{BH}, this integrates:

$$M_{\rm BH}(t) = M_i \left(1 - \frac{t}{\tau}\right)^{1/3} \qquad \tau \approx 0.4\,{\rm s}\left(\frac{M_i}{10^9\,{\rm g}}\right)^3 \left(\frac{108}{g_{\star,H}(T_{\rm BH})}\right)$$

Evaporation Timescales

- Since $\tau \sim s \times (M_i/10^9 g)^3$:

Evaporation Timescales

- Since $\tau \sim s \times (M_i/10^9 g)^3$:
    - $t_{univ} \sim 10^{18}$ s $\Longrightarrow$ black holes as (component of) stable relic DM must have $M_i \gtrsim 10^{15}$ g

Evaporation Timescales

- Since $\tau \sim s \times (M_i/10^9 g)^3$:
  - $t_{univ} \sim 10^{18}$ s $\Longrightarrow$ black holes as (component of) stable relic DM must have $M_i \gtrsim 10^{15}$ g
  - intermediate mass black holes constrained by CMB (Poulin et al. 1610.10051 & JCAP; Stöcker et al. 1801.01871 & JCAP) and BBN (Kohri and Yokoyama astro-ph/9908160 & PRD; Carr et al. 0912.5297 & PRD)

Evaporation Timescales

- Since $\tau \sim s \times (M_i/10^9 g)^3$:
  - $t_{univ} \sim 10^{18}$ s $\Longrightarrow$ black holes as (component of) stable relic DM must have $M_i \gtrsim 10^{15}$ g
  - intermediate mass black holes constrained by CMB (Poulin et al. 1610.10051 & JCAP; Stöcker et al. 1801.01871 & JCAP) and BBN (Kohri and Yokoyama astro-ph/9908160 & PRD; Carr et al. 0912.5297 & PRD)
  - black holes with $M_i \lesssim 10^9$ g evaporate pre-BBN

Evaporation Timescales

- Since $\tau \sim s \times (M_i/10^9 g)^3$:
  - $t_{univ} \sim 10^{18}$ s $\implies$ black holes as (component of) stable relic DM must have $M_i \gtrsim 10^{15}$ g
  - intermediate mass black holes constrained by CMB (Poulin et al. 1610.10051 & JCAP; Stöcker et al. 1801.01871 & JCAP) and BBN (Kohri and Yokoyama astro-ph/9908160 & PRD; Carr et al. 0912.5297 & PRD)
  - black holes with $M_i \lesssim 10^9$ g evaporate pre-BBN
- Can $M_i \lesssim 10^9$ g black holes impact our universe?

Black Hole Energy Density

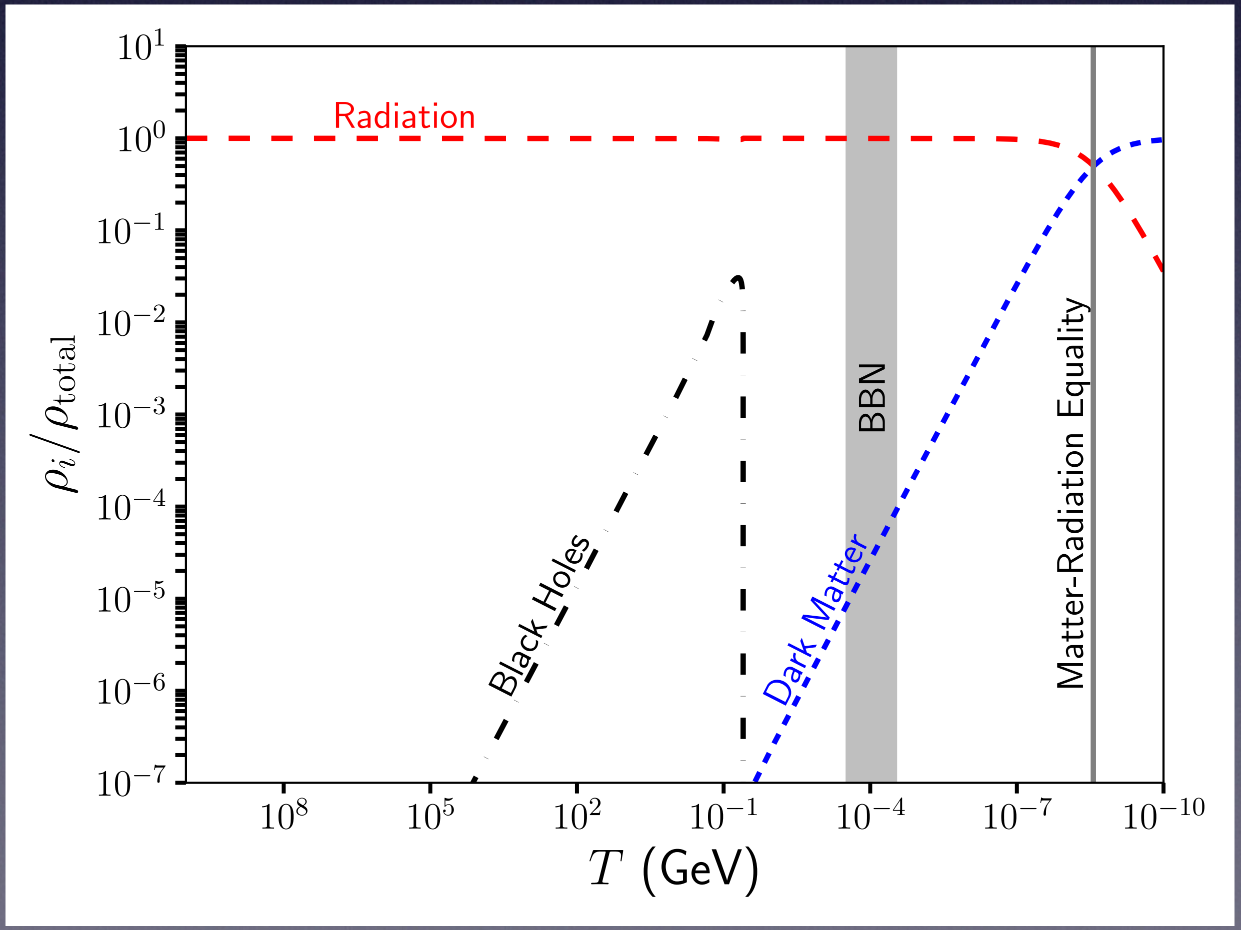
$\rho_{(SM)\ rad} \sim a^{-4}$, $\rho_{DM} \sim a^{-3}$

because of this, black holes will grow in relative importance over cosmic time

Black Hole Energy Density

$\rho_{(SM)\ rad} \sim a^{-4}$, $\rho_{DM} \sim a^{-3}$

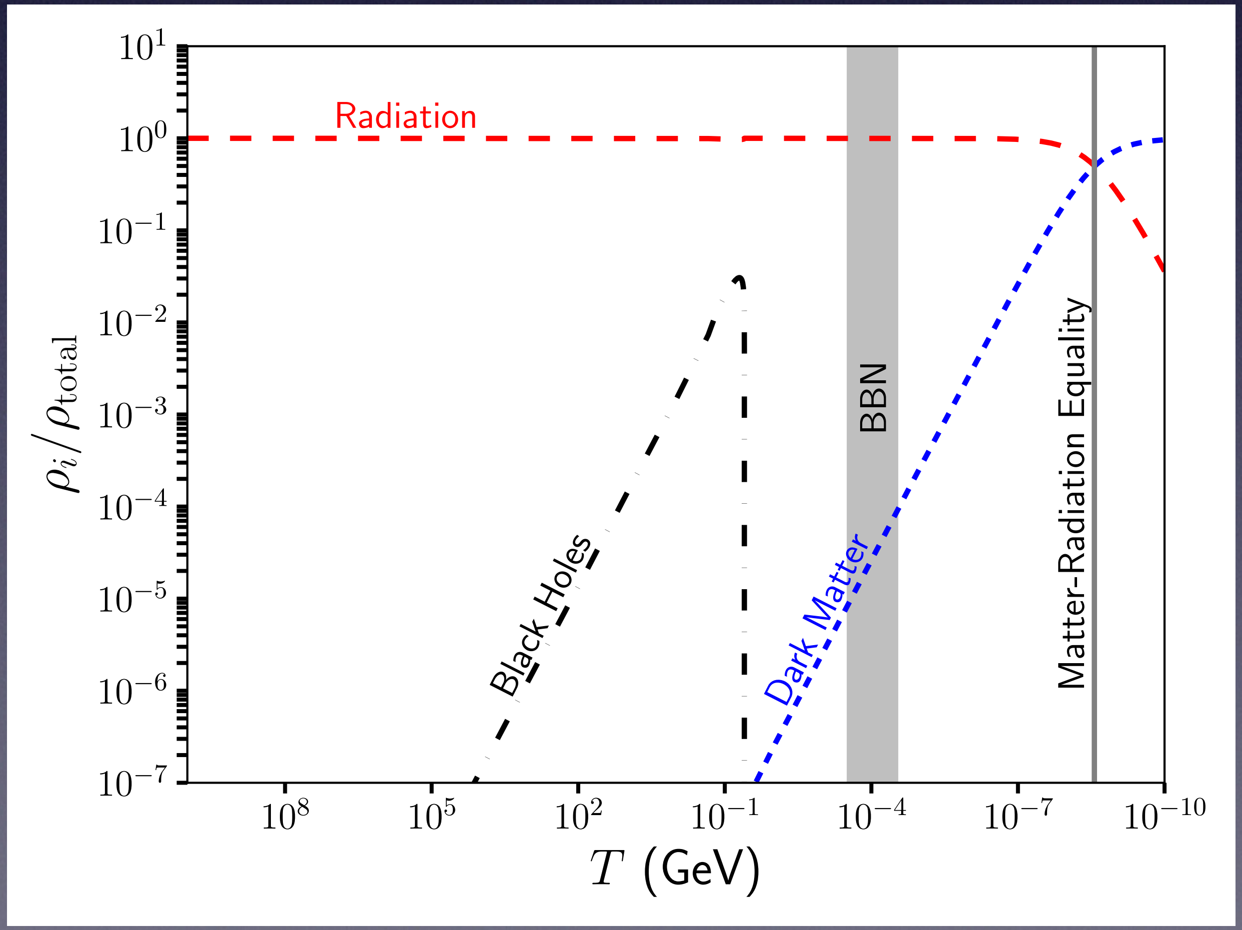
no domination



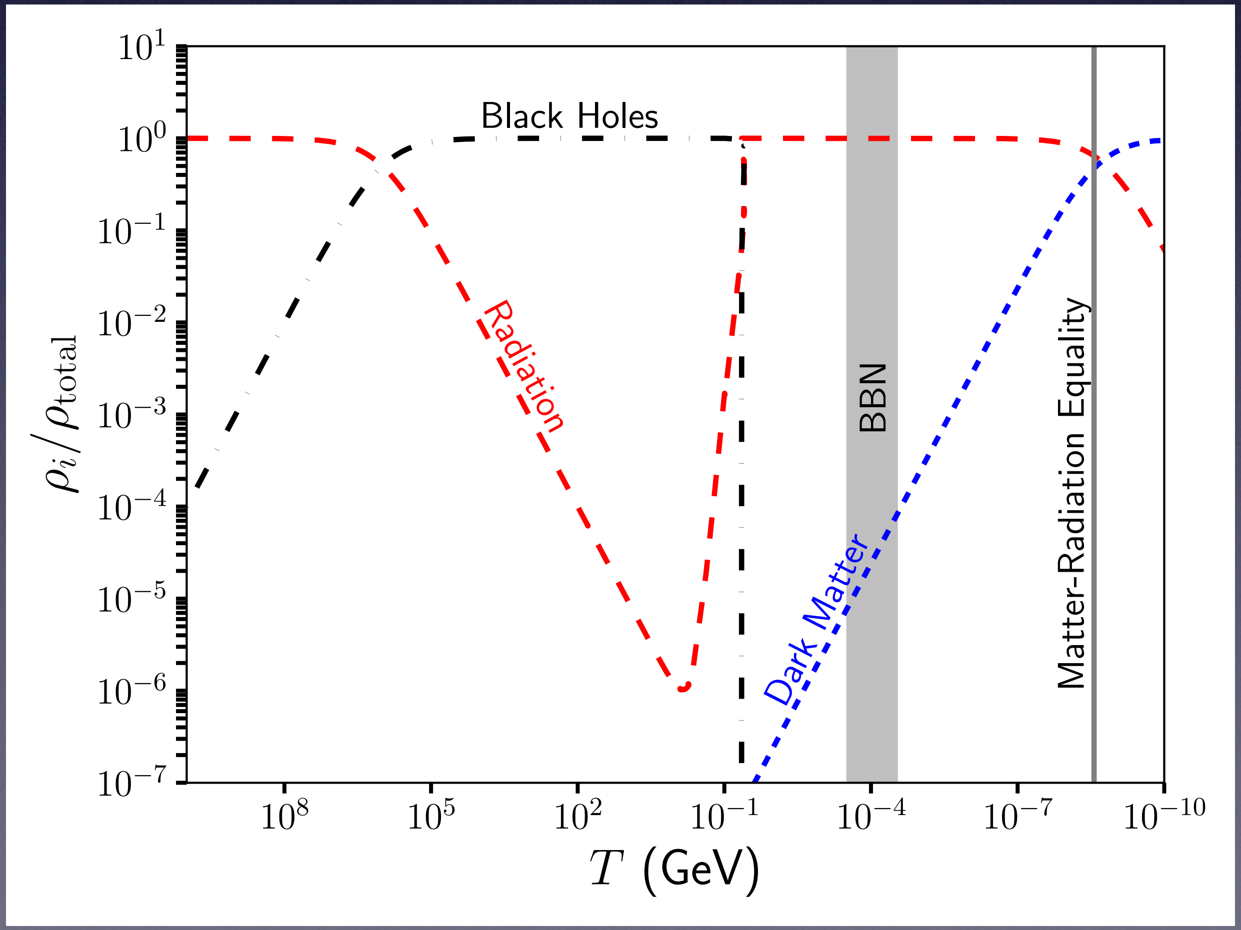
Black Hole Energy Density

$\rho_{(SM)\ rad} \sim a^{-4}$, $\rho_{DM} \sim a^{-3}$

no domination



black hole domination



Black Hole Reheating

$$T_\tau \simeq 40[50]\,\mathrm{MeV}\left(\frac{10^8\,\mathrm{g}}{M_i}\right)^{3/2}\left(\frac{g_{\star,H}(T_{\mathrm{BH}})}{108}\right)^{1/2}\left(\frac{14}{g_\star(T_\tau)}\right)^{1/4}$$

- It’s possible that black holes are the dominant source of the stuff in the universe

Black Hole Reheating

$$T_\tau \simeq 40[50]\,\mathrm{MeV}\left(\frac{10^8\,\mathrm{g}}{M_i}\right)^{3/2}\left(\frac{g_{\star,H}(T_{\mathrm{BH}})}{108}\right)^{1/2}\left(\frac{14}{g_\star(T_\tau)}\right)^{1/4}$$

- It's possible that black holes are the dominant source of the stuff in the universe
- Doesn't matter for the Standard Model — thermal equilibrium established before BBN

Black Hole Reheating

$$T_\tau \simeq 40[50]\,\mathrm{MeV}\left(\frac{10^8\,\mathrm{g}}{M_i}\right)^{3/2}\left(\frac{g_{\star,H}(T_{\mathrm{BH}})}{108}\right)^{1/2}\left(\frac{14}{g_\star(T_\tau)}\right)^{1/4}$$

- It’s possible that black holes are the dominant source of the stuff in the universe
- Doesn’t matter for the Standard Model — thermal equilibrium established before BBN
- Implications for dark sector?

Outline

1. The Mass Range of Primordial Black Holes
2. Dark Radiation
3. Superheavy Dark Matter
4. Concluding Comments

Dark Radiation, I

- Number of degrees of freedom in radiation at CMB is conventionally parameterized by $\Delta N_{\rm eff}$:

$$\Delta N_{\rm eff} \equiv \frac{8}{7}\left(\frac{11}{4}\right)^{4/3} \frac{\rho_X(T_{\rm CMB})}{\rho_\gamma(T_{\rm CMB})}$$

Dark Radiation, I

- Number of degrees of freedom in radiation at CMB is conventionally parameterized by $\Delta N_{\rm eff}$:

$$\Delta N_{\rm eff} \equiv \frac{8}{7}\left(\frac{11}{4}\right)^{4/3} \frac{\rho_X(T_{\rm CMB})}{\rho_\gamma(T_{\rm CMB})}$$

- Conservation of entropy and equipartition of energy (modulo graybody factors) gives:

$$\Delta N_{\rm eff} \equiv \frac{8}{7}\left(\frac{11}{4}\right)^{4/3} \frac{g_{H,X}}{\sum_{i\in{\rm SM}} g_{H,i}} \frac{g_{*,{\rm SM}}(T_{\rm RH})}{2} \left(\frac{g_{*S}^{\rm CMB}}{g_{*S}^{\rm RH}}\right)^{4/3}$$

Dark Radiation, I

- Number of degrees of freedom in radiation at CMB is conventionally parameterized by $\Delta N_{\rm eff}$:

$$\Delta N_{\rm eff} \equiv \frac{8}{7}\left(\frac{11}{4}\right)^{4/3} \frac{\rho_X(T_{\rm CMB})}{\rho_\gamma(T_{\rm CMB})}$$

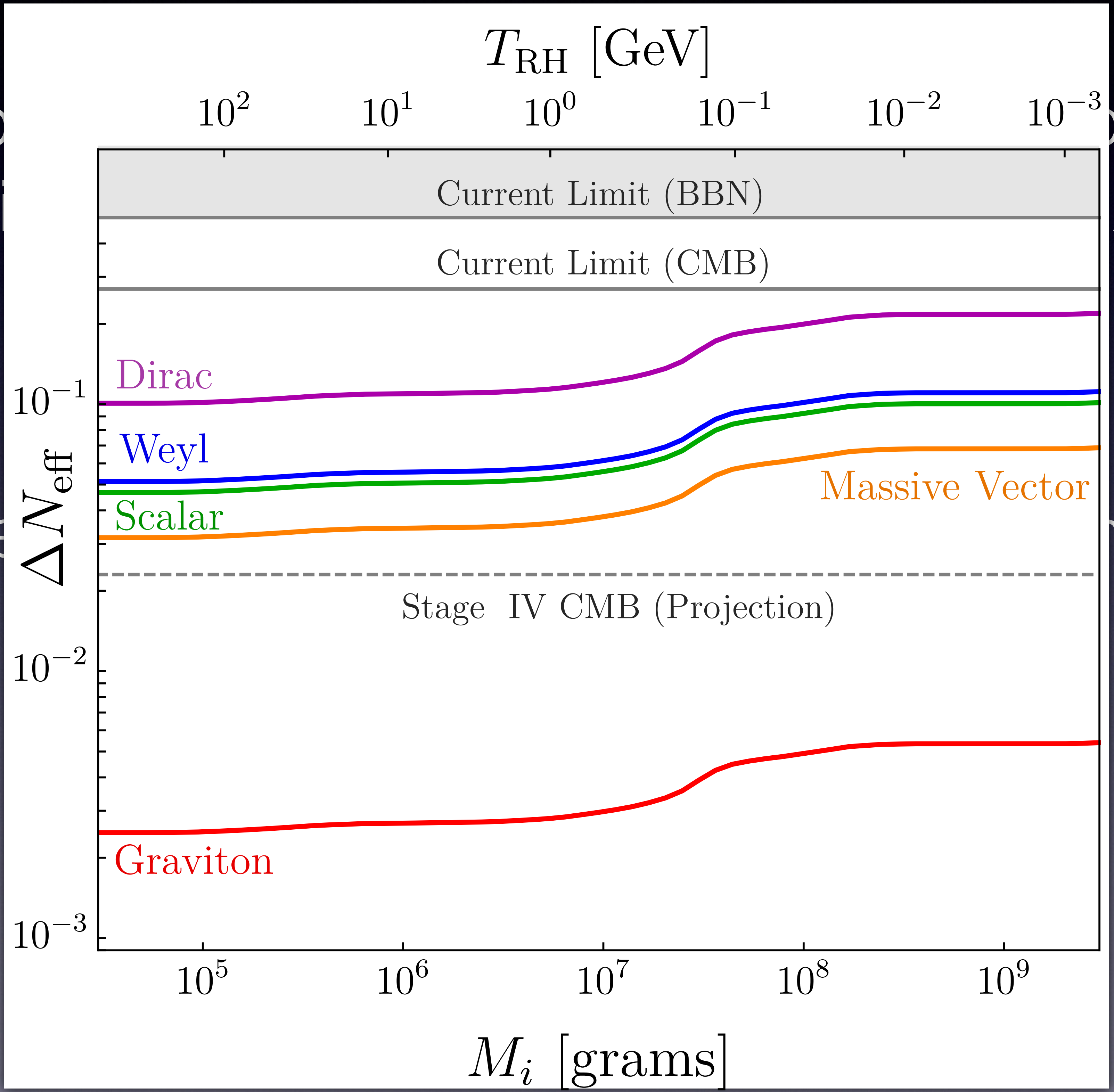
- Conservation of entropy and equipartition of energy (modulo graybody factors) gives:

$$\Delta N_{\rm eff} \approx 0.10 \left(\frac{g_{{\rm DR},H}}{4}\right)\left(\frac{106}{g_\star(T_{\rm RH})}\right)^{1/3}$$

Dark Radiation, I

- Numb… …on at CMB i… …ΔN_{eff}:

- Conse… …n of energ…



Dark Radiation, II

- How light must such a state be to be radiation?

$$\langle E_{\rm DR}\rangle\Big|_{\rm EQ} \simeq \alpha\, T_{{\rm BH},i} \times \frac{T_{\rm EQ}}{T_{\rm RH}}\left(\frac{g_\star(T_{\rm EQ})}{g_\star(T_{\rm RH})}\right)^{1/3}$$

$$\simeq 3.9\,{\rm MeV}\left(\frac{\alpha}{3.15}\right)\left(\frac{M_i}{10^8\,{\rm g}}\right)^{1/2}\left(\frac{108}{g_{\star,H}(T_{\rm BH})}\right)^{1/2}\left(\frac{14}{g_\star(T_{\rm RH})}\right)^{1/12}$$

Dark Radiation, II

- How light must such a state be to be radiation?

$$\langle E_{\rm DR}\rangle\Big|_{\rm EQ} \simeq \alpha\, T_{{\rm BH},i} \times \frac{T_{\rm EQ}}{T_{\rm RH}} \left(\frac{g_\star(T_{\rm EQ})}{g_\star(T_{\rm RH})}\right)^{1/3}$$

$$\simeq 3.9\,{\rm MeV} \left(\frac{\alpha}{3.15}\right)\left(\frac{M_i}{10^8\,{\rm g}}\right)^{1/2}\left(\frac{108}{g_{\star,H}(T_{\rm BH})}\right)^{1/2}\left(\frac{14}{g_\star(T_{\rm RH})}\right)^{1/12}$$

- Slight thermal distortion $\Longrightarrow$ $m_{DR} \lesssim 5$ MeV

Outline

1. The Mass Range of Primordial Black Holes
2. Dark Radiation
3. Superheavy Dark Matter
4. Concluding Comments

Black Hole Temperature

- Black hole has a temperature (Bekenstein 1973; Hawking 1974):

$$T_{\rm BH} = \frac{M_{\rm Pl}^2}{8\pi M_{\rm BH}}$$

Black Hole Temperature

- Black hole has a temperature (Bekenstein 1973; Hawking 1974):

$$T_{\mathrm{BH}} = \frac{M_{\mathrm{Pl}}^2}{8\pi M_{\mathrm{BH}}}$$

- As M_{BH} decreases, T_{BH} increases

Black Hole Temperature

- Black hole has a temperature (Bekenstein 1973; Hawking 1974):

$$T_{\rm BH} = \frac{M_{\rm Pl}^2}{8\pi M_{\rm BH}}$$

- As M_{BH} decreases, T_{BH} increases
- Continues until $T_{BH} \sim M_{Pl}$ (at which point Hawking's calculation breaks down)

Black Hole Temperature

- Black hole has a temperature (Bekenstein 1973; Hawking 1974):

$$T_{\rm BH} = \frac{M_{\rm Pl}^2}{8\pi M_{\rm BH}}$$

- As $M_{\rm BH}$
- Contin
Hawkin

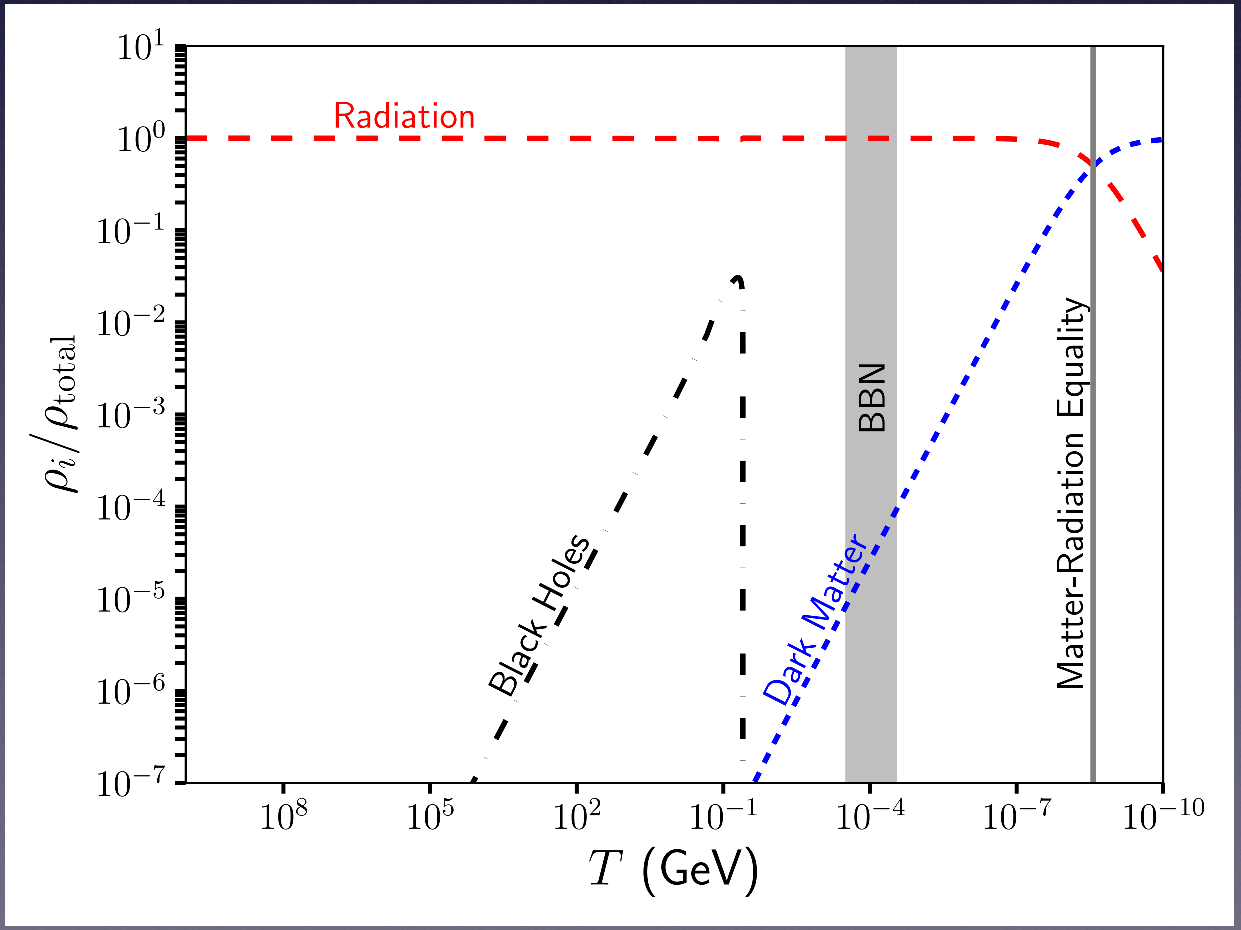
Eventually, particles of any sub-Planck scale mass can be produced in Hawking evaporation!

Heavy Dark Matter

Two different regimes:

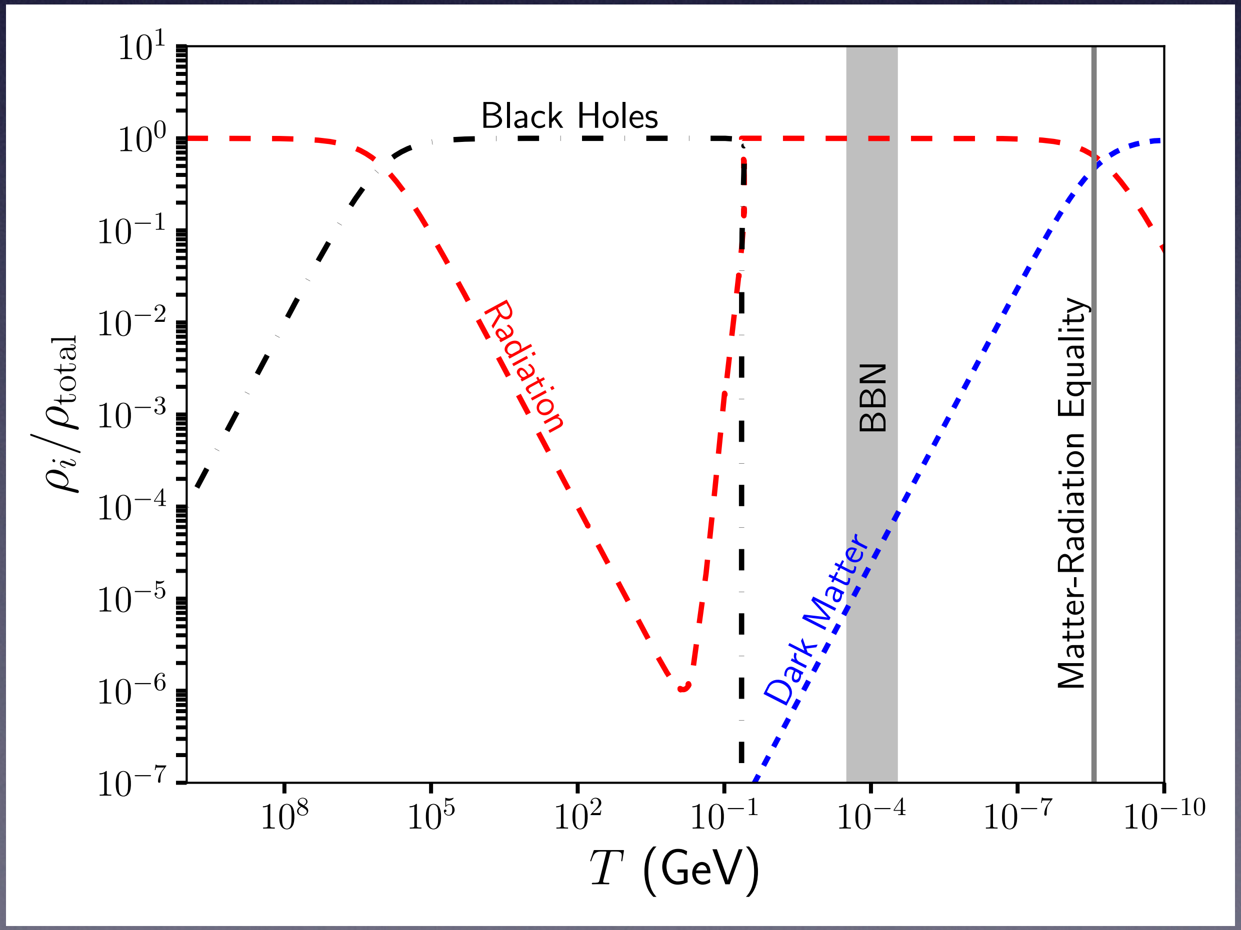
(see also Morrison et al., 1812.10606)

"freeze-in like"



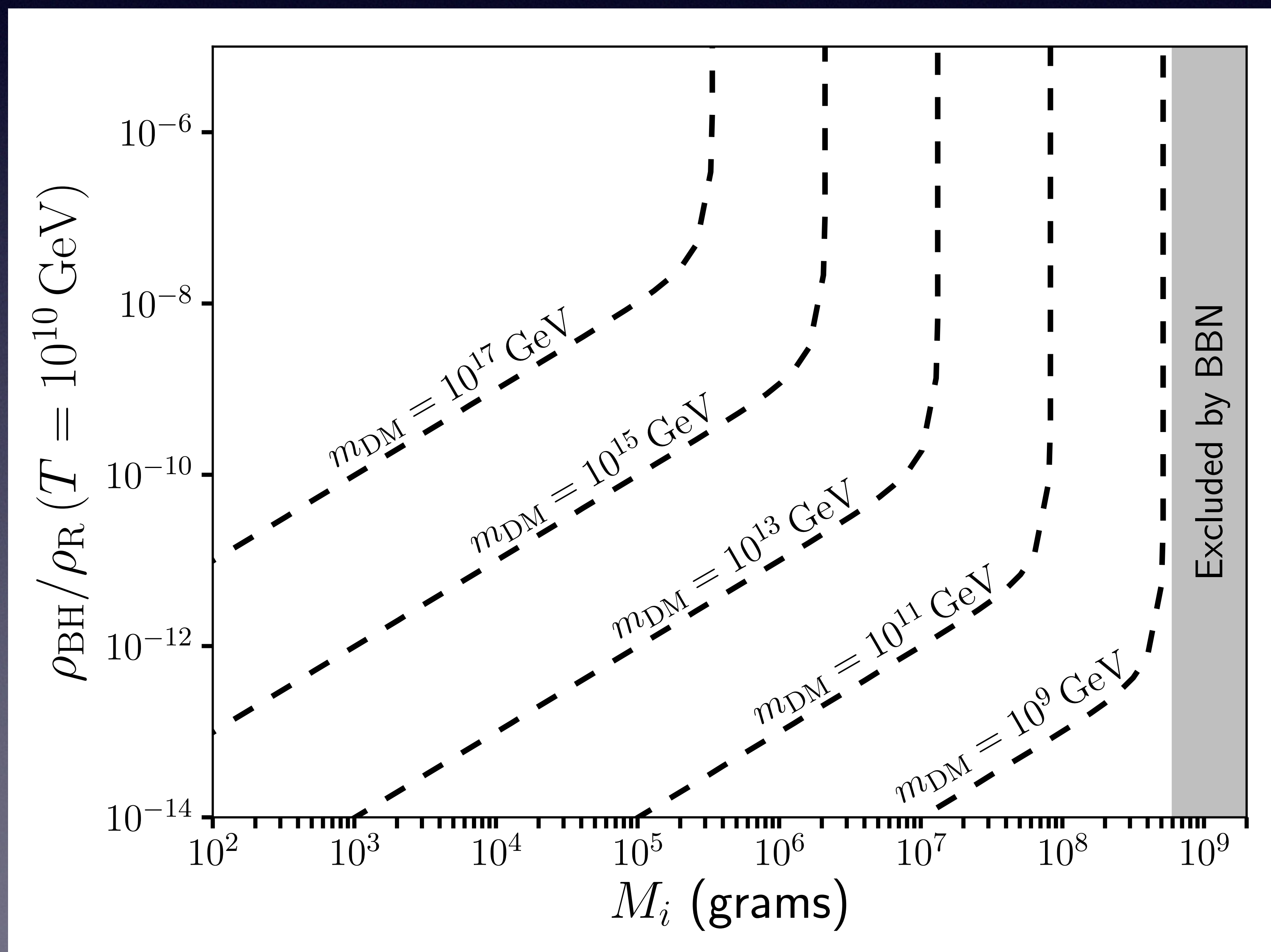
(see also Lennon et al., 1712.07664)

"freeze-out like"



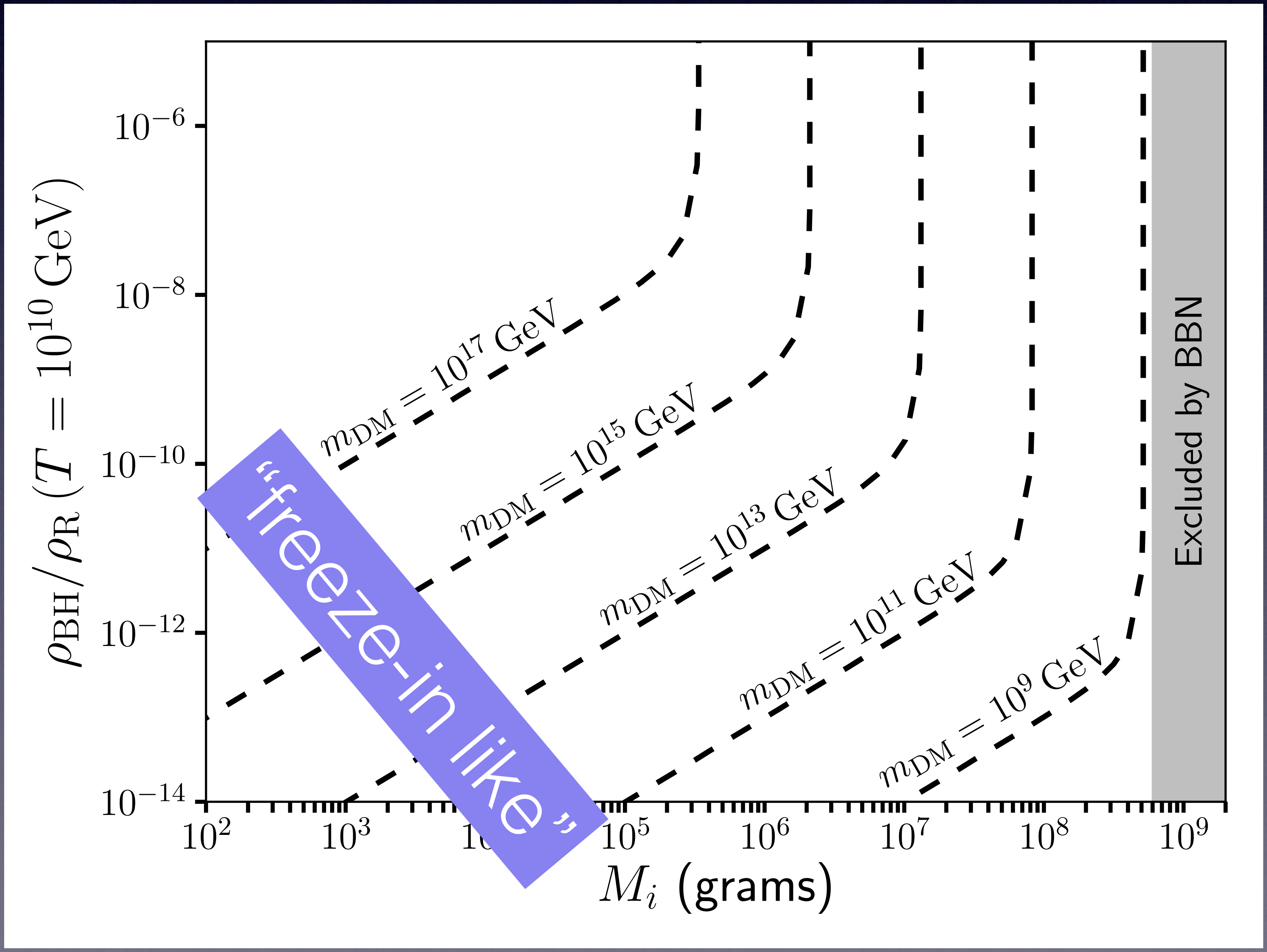
Heavy Dark Matter

Two different regimes:



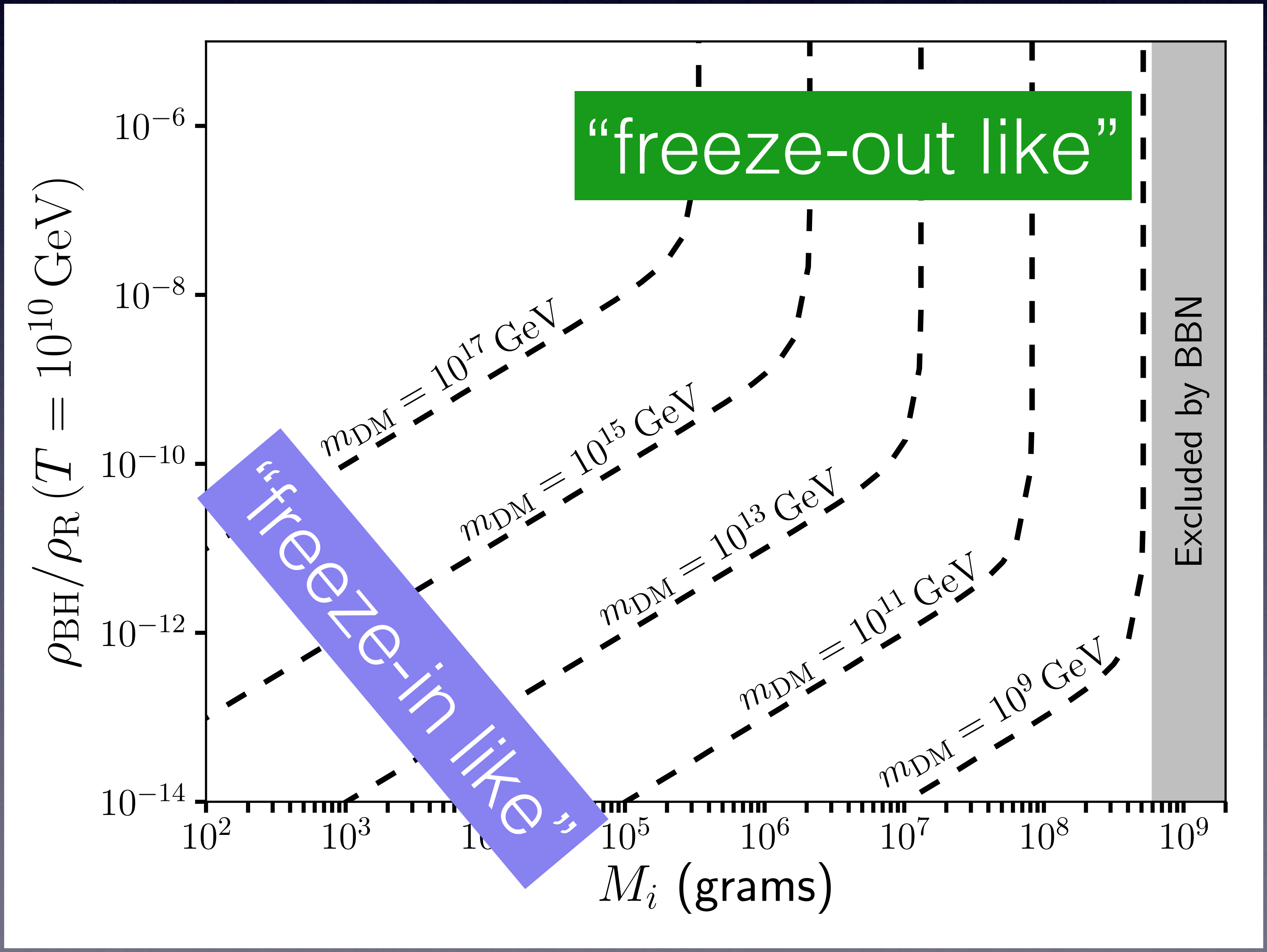
Heavy Dark Matter

Two different regimes:



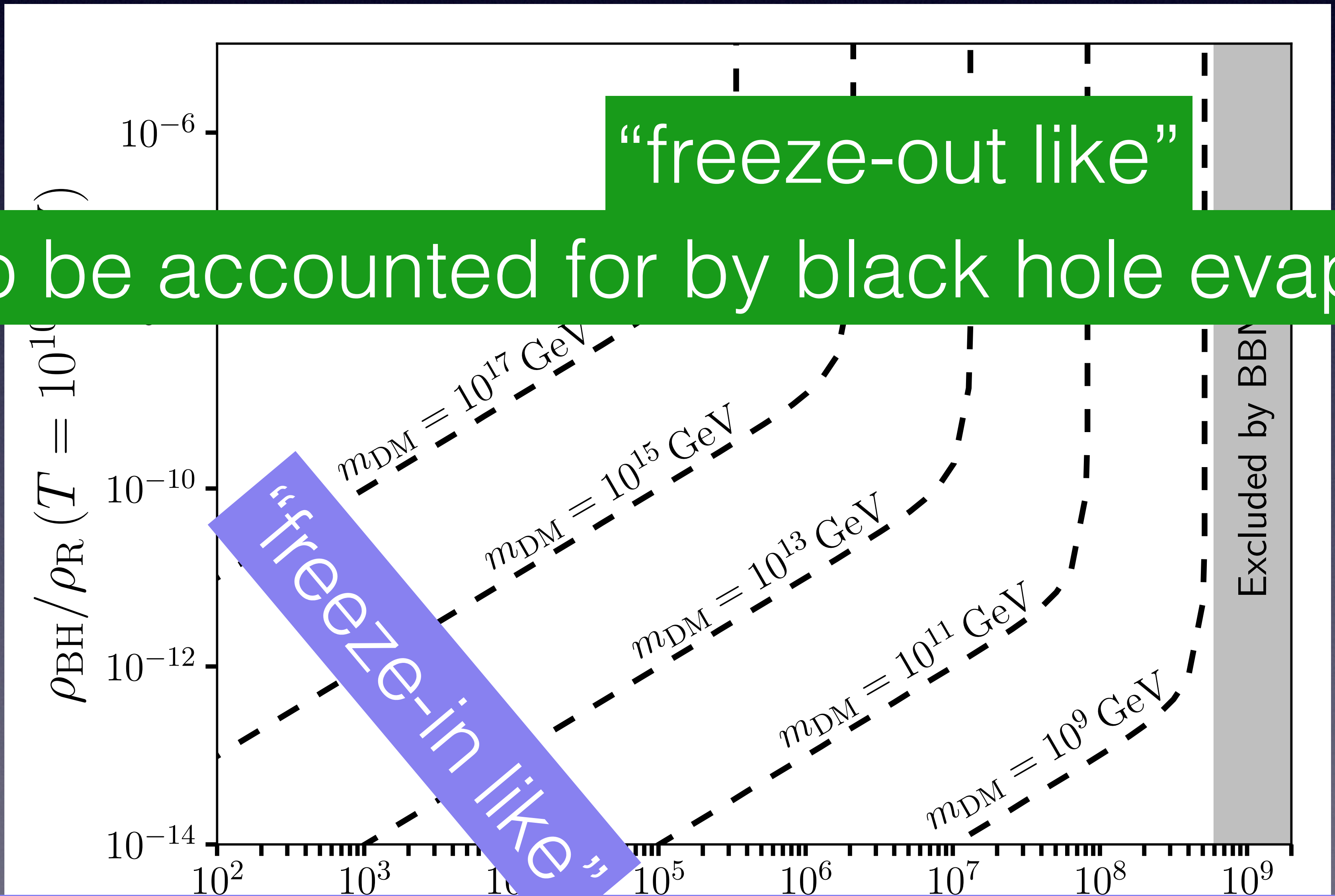
Heavy Dark Matter

Two different regimes:



Heavy Dark Matter

Two different regimes:



η_b needs to be accounted for by black hole evap. as well

η_b can be set by initial conditions / very early universe

Outline

1. The Mass Range of Primordial Black Holes
2. Dark Radiation
3. Superheavy Dark Matter
4. Effects on BBN and CMB
5. Concluding Comments

Some Things You Might Worry About

(Very) early universe conditions:

Some Things You Might Worry About

(Very) early universe conditions:

- formation of binaries

Some Things You Might Worry About

(Very) early universe conditions:

- formation of binaries
- gravitational wave inspiral

Some Things You Might Worry About

(Very) early universe conditions:

- formation of binaries
- gravitational wave inspiral
- accretion of SM stuff

Accretion

Bondi-Hoyle accretion…

Bondi, 1952 MNRAS

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

Accretion

Bondi-Hoyle accretion…

Bondi, 1952 MNRAS

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

…slowing / halting the evaporation process?

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

Future Directions

- Interesting possibility for a “nightmare-scenario” decoupled dark sector
- Potentially observable in CMBS4
- Early-universe physics can be treated in greater depth in UV-complete scenarios
- Possibilities for more extended hidden sectors?

Thanks!

Extra

1. Mass Function
2. Effects on BBN and CMB

Black hole mergers

Binary capture in the early universe…

$$\sigma_{\rm bc} = \pi \left(\frac{85\pi}{3} \right)^{2/7} r_{\rm Schw}^2 v^{-18/7}$$

Quinlan and Shapiro, 1989 ApJ

Binary Formation During Black Hole Domination

Binary capture in the early universe…

Quinlan and Shapiro, 1989 ApJ

$$\sigma_{\rm bc} = \pi \left(\frac{85\pi}{3}\right)^{2/7} r_{\rm Schw}^2 v^{-18/7}$$

Black hole domination:

$$\frac{\Gamma}{H} \sim \frac{\rho_{\rm BH} M_{\rm BH}}{M_{\rm Pl}^4} \frac{M_{\rm Pl}}{\sqrt{\rho_{\rm BH}}} \sim \sqrt{\frac{\rho_{\rm BH}}{M_{\rm Pl}^4} \frac{M_{\rm BH}}{M_{\rm Pl}}}$$

Binary Formation During Black Hole Domination

Binary capture in the early universe…

Quinlan and Shapiro, 1989 ApJ

$$\sigma_{\rm bc} = \pi \left(\frac{85\pi}{3} \right)^{2/7} r_{\rm Schw}^2 v^{-18/7}$$

Black hole domination:

$$\frac{\Gamma}{H} \sim \frac{\rho_{\rm BH} M_{\rm BH}}{M_{\rm Pl}^4} \frac{M_{\rm Pl}}{\sqrt{\rho_{\rm BH}}} \sim \sqrt{\frac{\rho_{\rm BH}}{M_{\rm Pl}^4}} \frac{M_{\rm BH}}{M_{\rm Pl}}$$

can be ~1

Binary Formation During Black Hole Domination

Binary capture in the early universe…

Quinlan and Shapiro, 1989 ApJ

$$\sigma_{\rm bc} = \pi \left(\frac{85\pi}{3}\right)^{2/7} r_{\rm Schw}^2 v^{-18/7}$$

Black hole domination:

$$\frac{\Gamma}{H} \sim \frac{\rho_{\rm BH} M_{\rm BH}}{M_{\rm Pl}^4} \frac{M_{\rm Pl}}{\sqrt{\rho_{\rm BH}}} \sim \sqrt{\frac{\rho_{\rm BH}}{M_{\rm Pl}^4}} \frac{M_{\rm BH}}{M_{\rm Pl}}$$

always ≫1

Binary Formation During Radiation Domination

Binary capture in the early universe…

Quinlan and Shapiro, 1989 ApJ

$$\sigma_{\rm bc} = \pi \left(\frac{85\pi}{3}\right)^{2/7} r_{\rm Schw}^2 v^{-18/7}$$

$$\frac{\Gamma_{\rm bc}}{H} \approx 0.02 \times \left(\frac{M_{\rm BH}}{10^8\,{\rm g}}\right) \left(\frac{T_{\rm eff}}{10^7\,{\rm GeV}}\right)^2 \left(\frac{v}{10^{-5}}\right)^{-11/7} \left(\frac{\rho_{\rm BH}}{\rho_{\rm tot}}\right)$$

Inspiral

Binary capture in the early universe…

Quinlan and Shapiro, 1989 ApJ

$$\sigma_{\rm bc} = \pi \left(\frac{85\pi}{3}\right)^{2/7} r_{\rm Schw}^2 v^{-18/7}$$

$$\frac{\Gamma_{\rm bc}}{H} \approx 0.02 \times \left(\frac{M_{\rm BH}}{10^8\,{\rm g}}\right)\left(\frac{T_{\rm eff}}{10^7\,{\rm GeV}}\right)^2 \left(\frac{v}{10^{-5}}\right)^{-11/7} \left(\frac{\rho_{\rm BH}}{\rho_{\rm tot}}\right)$$

…leading to mergers?

$$t_{\rm insp} = \frac{5a_0^4}{512 G^3 M_{\rm BH}^3} \qquad \frac{t_{\rm insp}}{\tau} \simeq 10 \times \zeta^4 \left(\frac{10^8\,{\rm GeV}}{T_{\rm eff}}\right)^8 \left(\frac{10^8{\rm g}}{M_{\rm BH}}\right)^6$$

Peters, 1964 Phys Rev

Black Hole Temperature

- Black hole has a temperature (Bekenstein 1973; Hawking 1974):

$$T_{\rm BH} = \frac{M_{\rm Pl}^2}{8\pi M_{\rm BH}}$$

Black Hole Temperature

- Black hole has a temperature (Bekenstein 1973; Hawking 1974):

$$T_{\rm BH} = \frac{M_{\rm Pl}^2}{8\pi M_{\rm BH}}$$

- As M_{BH} decreases, T_{BH} increases

Black Hole Temperature

- Black hole has a temperature (Bekenstein 1973; Hawking 1974):

$$T_{\rm BH} = \frac{M_{\rm Pl}^2}{8\pi M_{\rm BH}}$$

- As M_{BH} decreases, T_{BH} increases
- Continues until $T_{BH} \sim M_{Pl}$ (at which point Hawking's calculation breaks down)

Black Hole Temperature

- Black hole has a temperature (Bekenstein 1973; Hawking 1974):

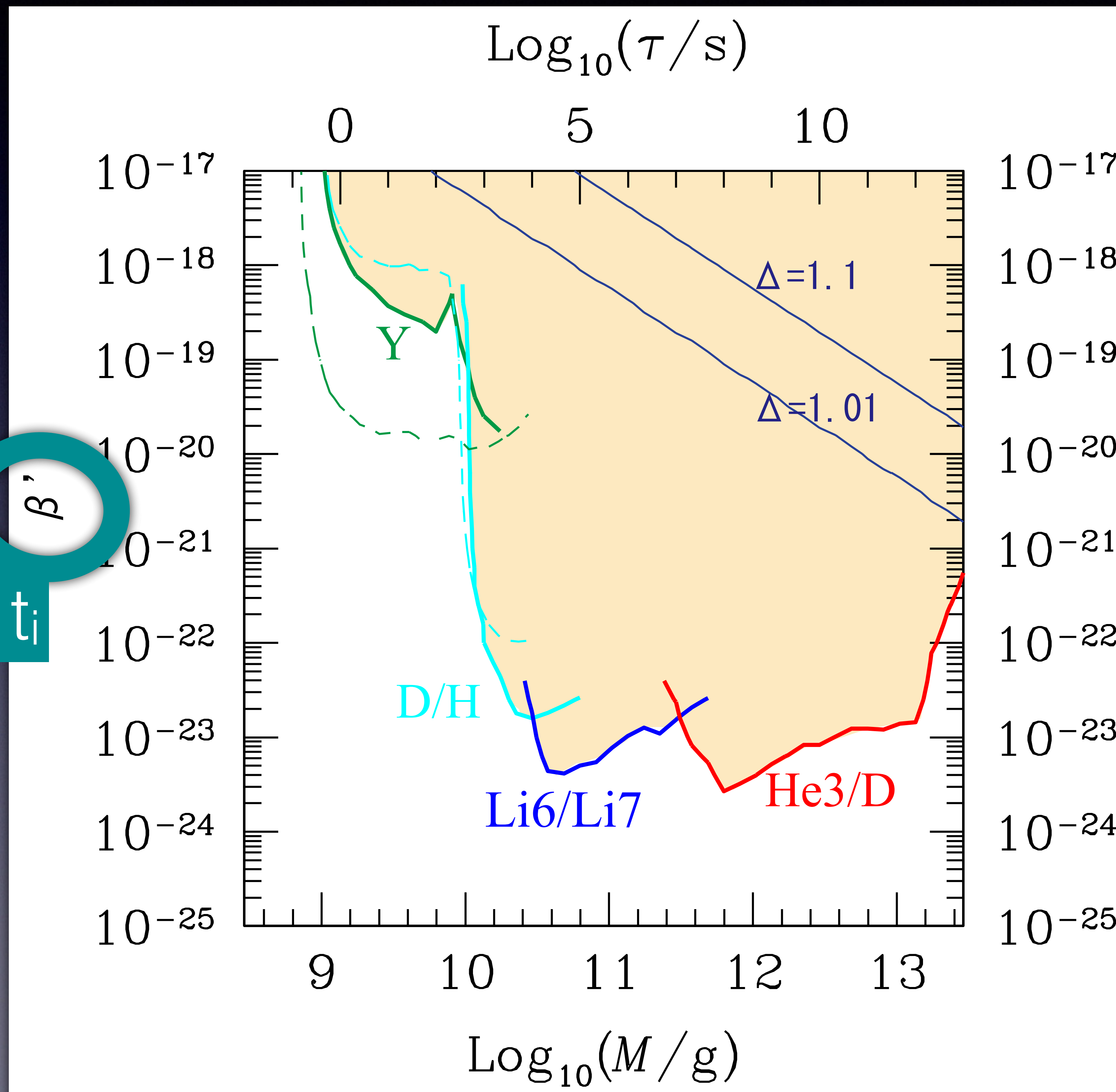
$$T_{\rm BH} = \frac{M_{\rm Pl}^2}{}$$

- As $M_{\rm B}$

- Conti
Hawk

High energy particles
(strongly interacting or not)
can impact n/p freezeout,
break up nuclei, etc.!

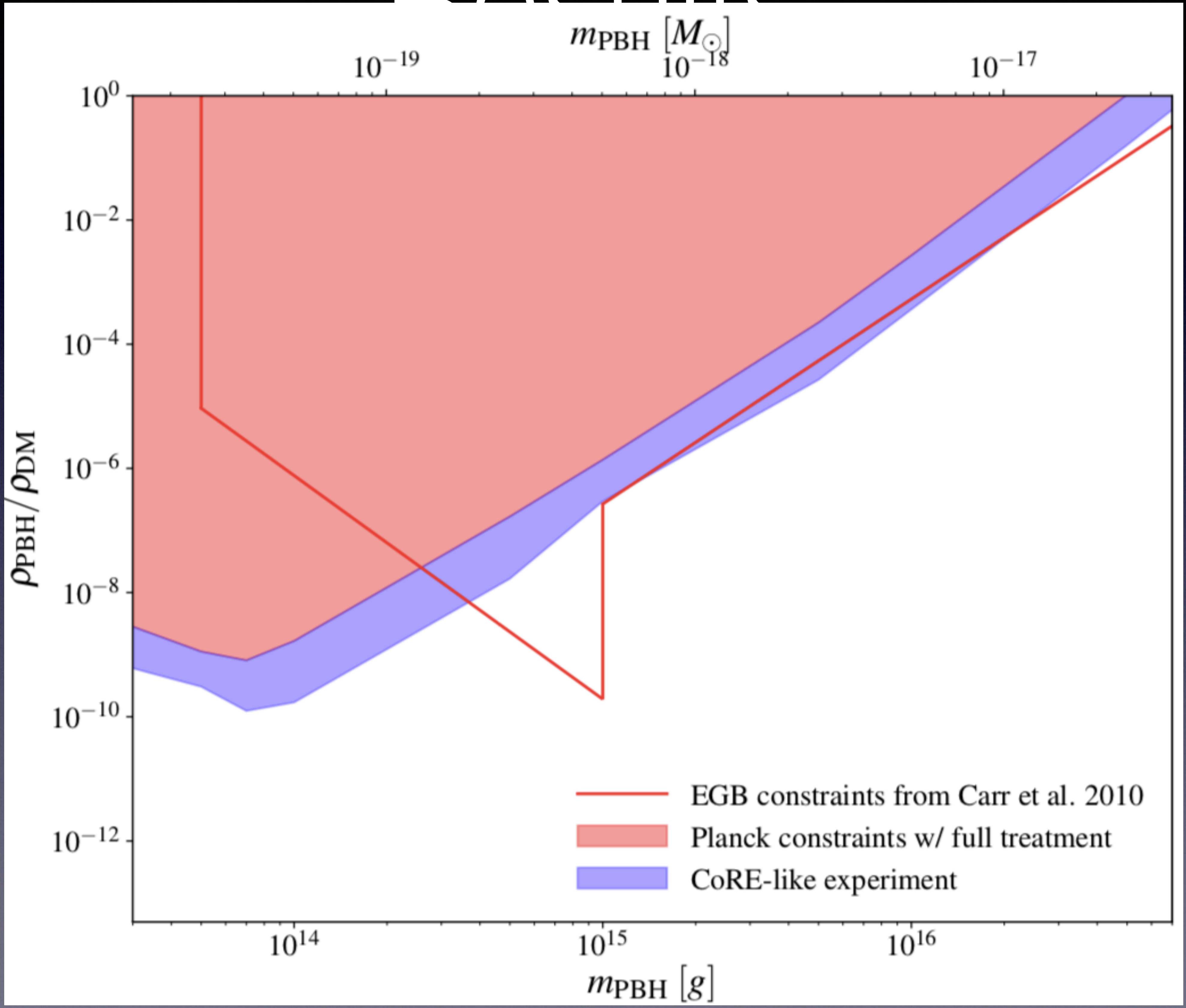
Results



ρ_{BH}/ρ_{SM} at t_i

Carr, Kohri, Sendouda, Yokoyama, 0912.5297 & PRD

Results



Stöcker, Krämer, Lesgourgues, Poulin, 1801.01871 & JCAP

Next Steps

- Updated observations and nuclear rates

Next Steps

- Updated observations and nuclear rates
- Effects on CMB spectral distortions

Next Steps

- Updated observations and nuclear rates
- Effects on CMB spectral distortions
- Large number of extra sectors (N-naturalness)
    - will change the mass / lifetime relation
    - smaller fraction of energy going to SM stuff