Asymmetric Reheating by Primordial Black Holes

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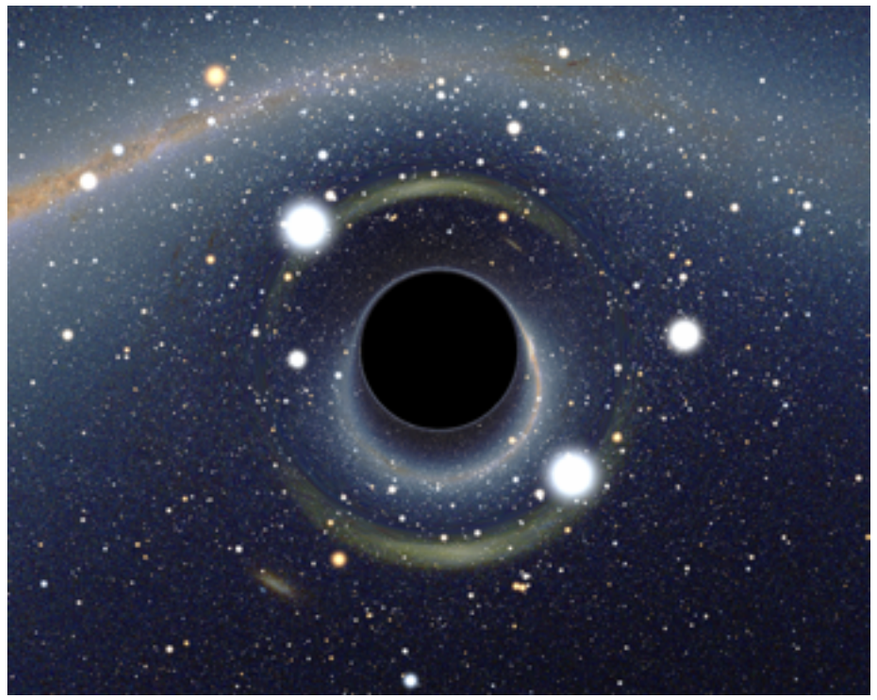
DM exists (Gravitational Evidence):
Rotation curves, CMB, Structure formation, Gravitational lensing

null result of search for possible non-gravitational interactions of DM: motivates idea of dark sectors coupled only gravitationally to visible sector.

challenge: populating the dark sector

Example:
reheating by inflaton, populating both dark and visible sectors.
but two sectors can communicate by exchanging inflaton, possibility of thermalization, washes out initial asymmetry in temperatures.

Novel mechanism:
Hawking evaporation of PBHs!



Populating a dark sector by relativistic and far from equilibrium particles:

$$\mathcal{L} = \frac{1}{2}\partial_\mu\chi\partial^\mu\chi - \frac{1}{2}m_\chi\chi^2 - \frac{m_\chi\lambda}{3!}\chi^3 - \frac{\lambda^2}{4!}\chi^4 \qquad 1 \lesssim \lambda \lesssim 4\pi$$

populating: $t = \tau : n_\chi(\tau), \rho_\chi(\tau)$

particles become non-relativistic: $t = t_m : \bar{E}_\chi \sim m_\chi$

toward equilibrium:

kinetic equilibrium:

elastic scattering processes, lead to a temperature and non-zero chemical potential

$$\frac{\Gamma_{\chi,2\to2}(t)}{H(t)} \sim \frac{n_\chi(t)/\bar{E}_\chi(t)^2}{H(t)} = \frac{\Gamma_{\chi,2\to2}(\tau)}{H(\tau)} \begin{cases} \frac{T_V(\tau)}{T_V(t)} & \tau \le t \le t_m \\ \frac{T_V(\tau)}{T_V(t_m)}\frac{T_V(t)}{T_V(t_m)} & t > t_m, \end{cases}$$

Chemical equilibrium:

number changing processes, give rise to a temperature and zero chemical potential

$$\frac{\Gamma_{\chi,2\to3}(t)}{H(t)} \sim a^3$$

decoupling: $t = t_{\rm dec}$

redshift

conservation of entropy

$$\rho_\chi(\tau) \longrightarrow \rho_{\chi,\mathrm{rel}}(t_{\mathrm{eq}}) = \frac{\pi^2}{30} g_{*,\chi} T_{\chi,\mathrm{rel}}(t_{\mathrm{eq}})^4 \longrightarrow T_V(t_m)$$

$$\frac{\Gamma_{\chi,3\to2}(t_m)}{H(t_m)} < 1$$

no cannibalism, decoupling

$$\frac{\Gamma_{\chi,3\to2}(t_m)}{H(t_m)} \geq 1$$

cannibalism, then decoupling

redshift

$$\rho_\chi(\tau) \longrightarrow \rho_{\chi,\text{non-rel}}(t_{\mathrm{eq}}) = m_\chi n_{\chi,\text{non-rel}}(t_{\mathrm{eq}})$$

$$n_{\chi,\text{non-rel}}(t_{\mathrm{eq}}) = g_{*,\chi} \left(\frac{m_\chi T_{\chi,\text{non-rel}}(t_{\mathrm{eq}})}{2\pi} \right)^{3/2} e^{-m_\chi / T_{\chi,\text{non-rel}}(t_{\mathrm{eq}})}$$

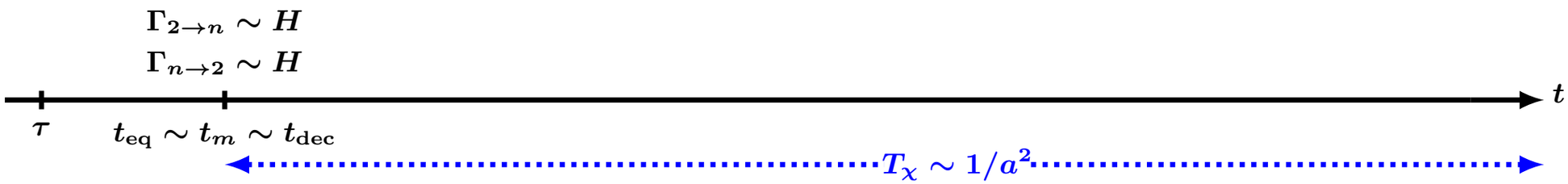
$$\frac{\Gamma_{\chi,3\to2}(t_{\mathrm{eq}})}{H(t_{\mathrm{eq}})} < 1$$

no cannibalism, decoupling

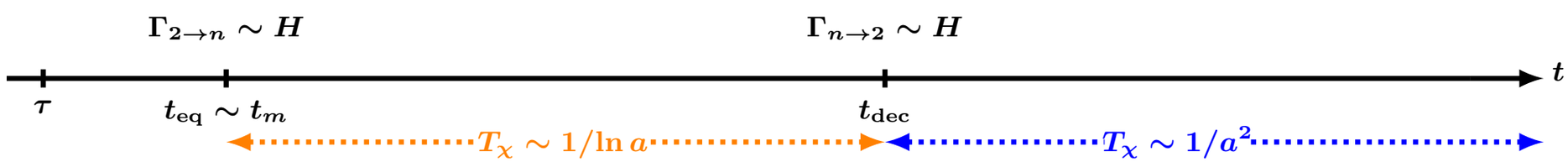
$$\frac{\Gamma_{\chi,3\to2}(t_{\mathrm{eq}})}{H(t_{\mathrm{eq}})} \geq 1$$

cannibalism, then decoupling

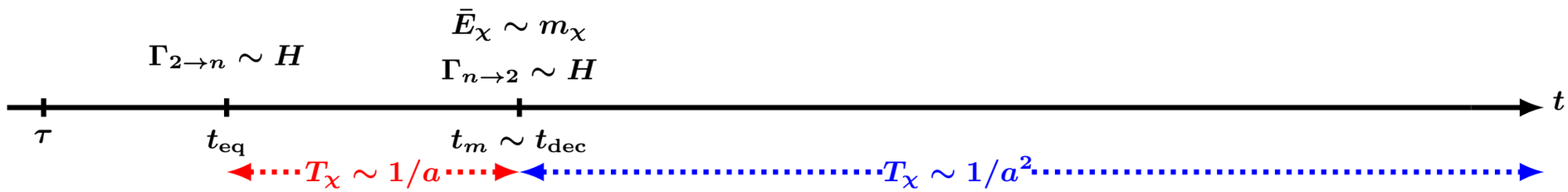
non-relativistic, no cannibalism:



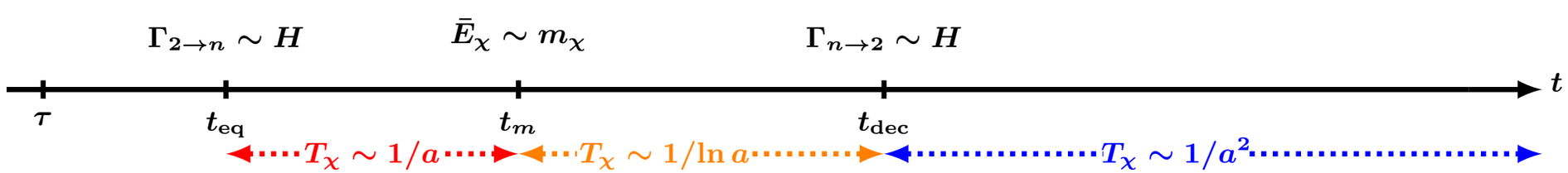
non-relativistic, with cannibalism:



relativistic, no cannibalism



relativistic, with cannibalism



PBHs: motivated by many different scenarios

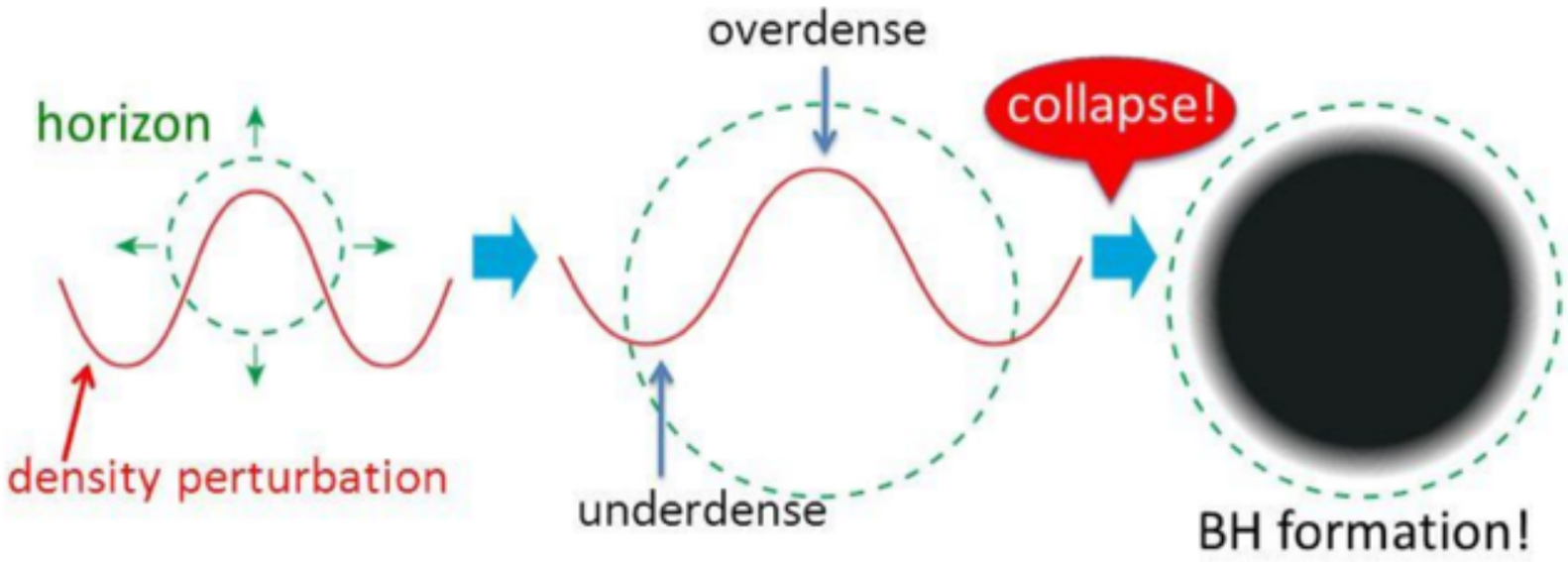


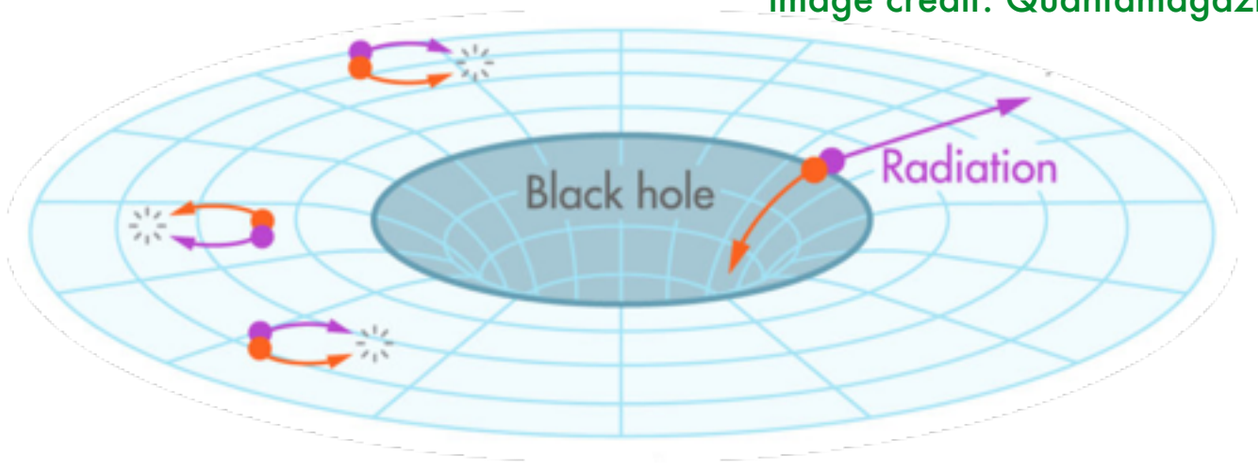
image credit: https://slideplayer.com/slide/7773485/

BHs can be fully characterized by their mass, spin, and charge

formed in a radiation-dominated era:
mass: of the order of the horizon mass, spin negligible

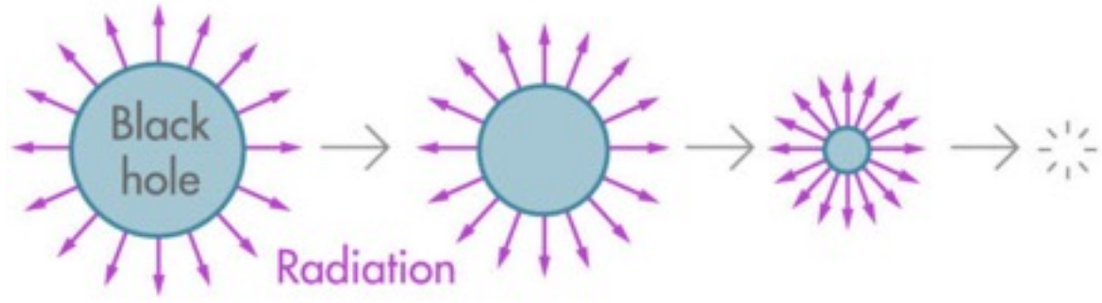
Hawking evaporation:

image credit: Quantamagazine



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

$$\frac{d^2 u_i(E,t)}{dt dE} = \frac{g_i}{8\pi^2} \frac{E^3}{e^{E/T_{\rm BH}} \pm 1}$$



$$M(t) = M_i \left(1 - \frac{(t-t_i)}{\tau}\right)^{1/3}, \qquad \tau = \frac{10240\pi}{g_*(T_{\rm BH})} \frac{M_i^3}{M_{\rm Pl}^4}$$

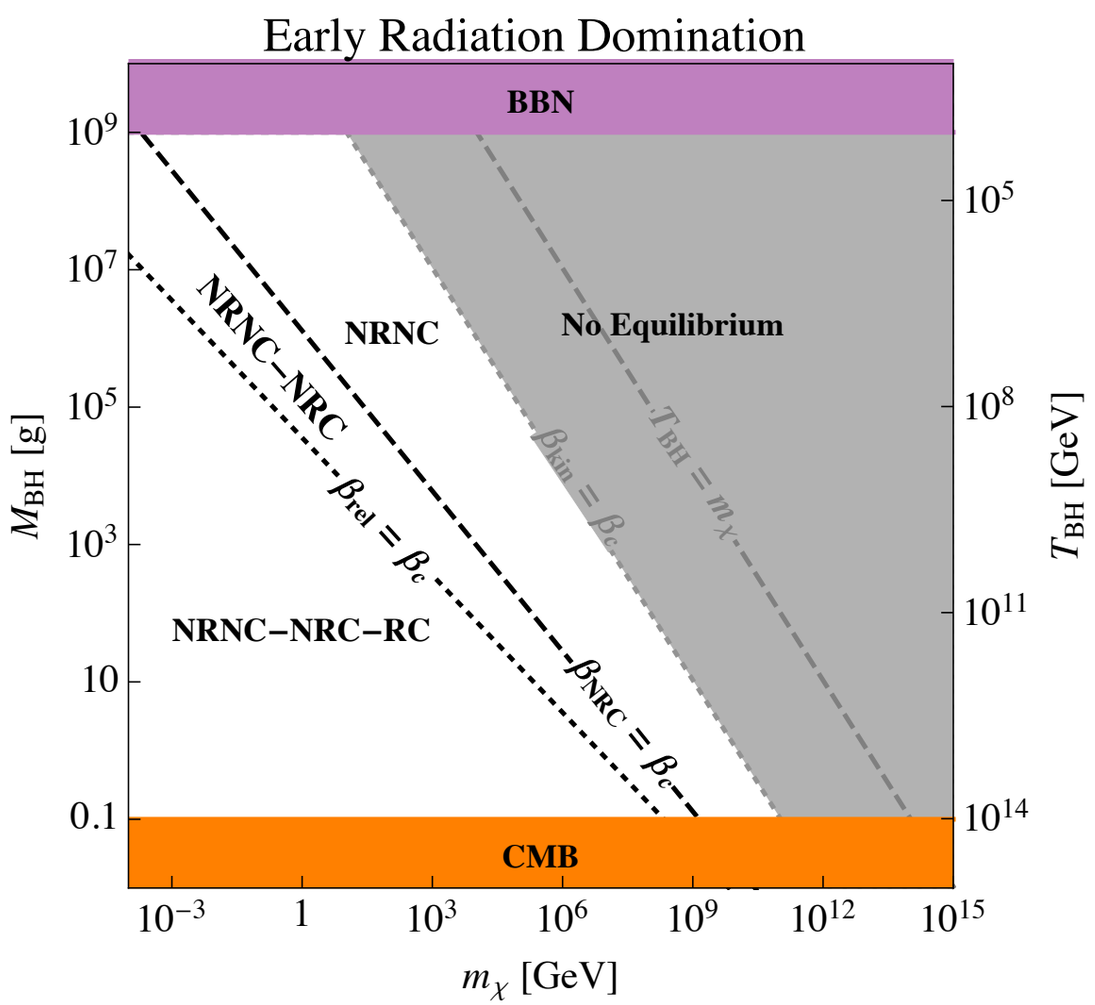
$$N_i = \frac{120\,\zeta(3)}{\pi^3} \frac{g_i}{g_*(T_{\rm BH})} \frac{M_{\rm BH}^2}{M_{\rm Pl}^2}, \qquad T_{\rm BH} > m_i$$

$$N_i = \frac{15\,\zeta(3)}{8\pi^5} \frac{g_i}{g_*(T_{\rm BH})} \frac{M_{\rm Pl}^2}{m_i^2}, \qquad T_{\rm BH} < m_i$$

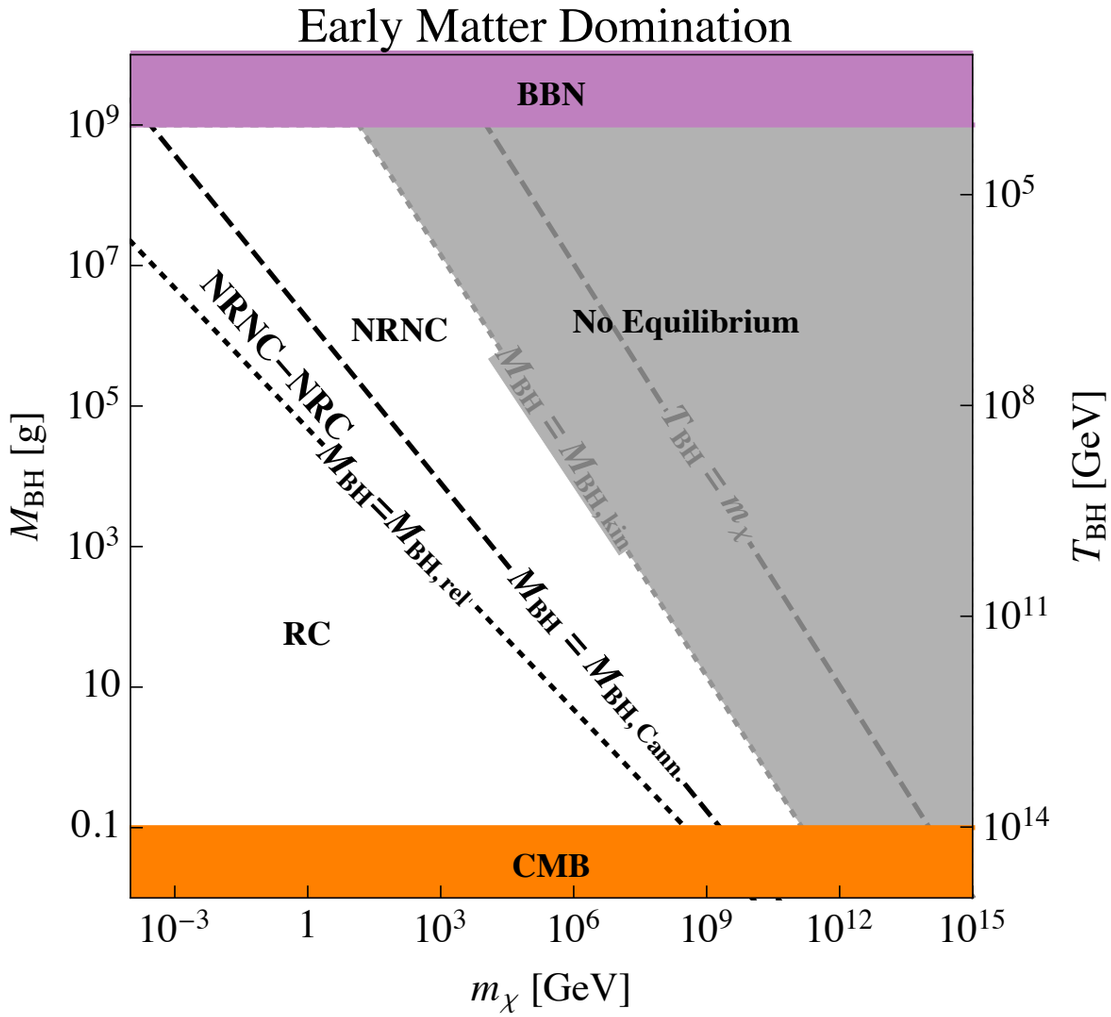
$0.1\,\mathrm{g} \lesssim M_{\rm BH} \lesssim 10^9\,\mathrm{g}$ **evaporate before BBN, not constrained**

$$\beta \equiv \frac{\rho_{\rm BH}(t_{\rm f})}{\rho_{\rm R}(t_{\rm f})}$$

Thermal History	PBHs Initial Abundance
NRNC (non-relativistic, no cannibalism)	$\beta_{\rm kin} \lesssim \beta \lesssim \beta_{\rm NRC}$
NRC (non-relativistic, cannibalism)	$\beta_{\rm NRC} \lesssim \beta \lesssim \beta_{\rm rel}$
RNC (relativistic, no cannibalism)	$\beta_{\rm rel} \lesssim \beta \lesssim \beta_{\rm RC}$
RC (relativistic, cannibalism)	$\beta_{\rm RC} \lesssim \beta \lesssim \beta_{\rm crit}$



$\beta < \beta_{\rm crit}$

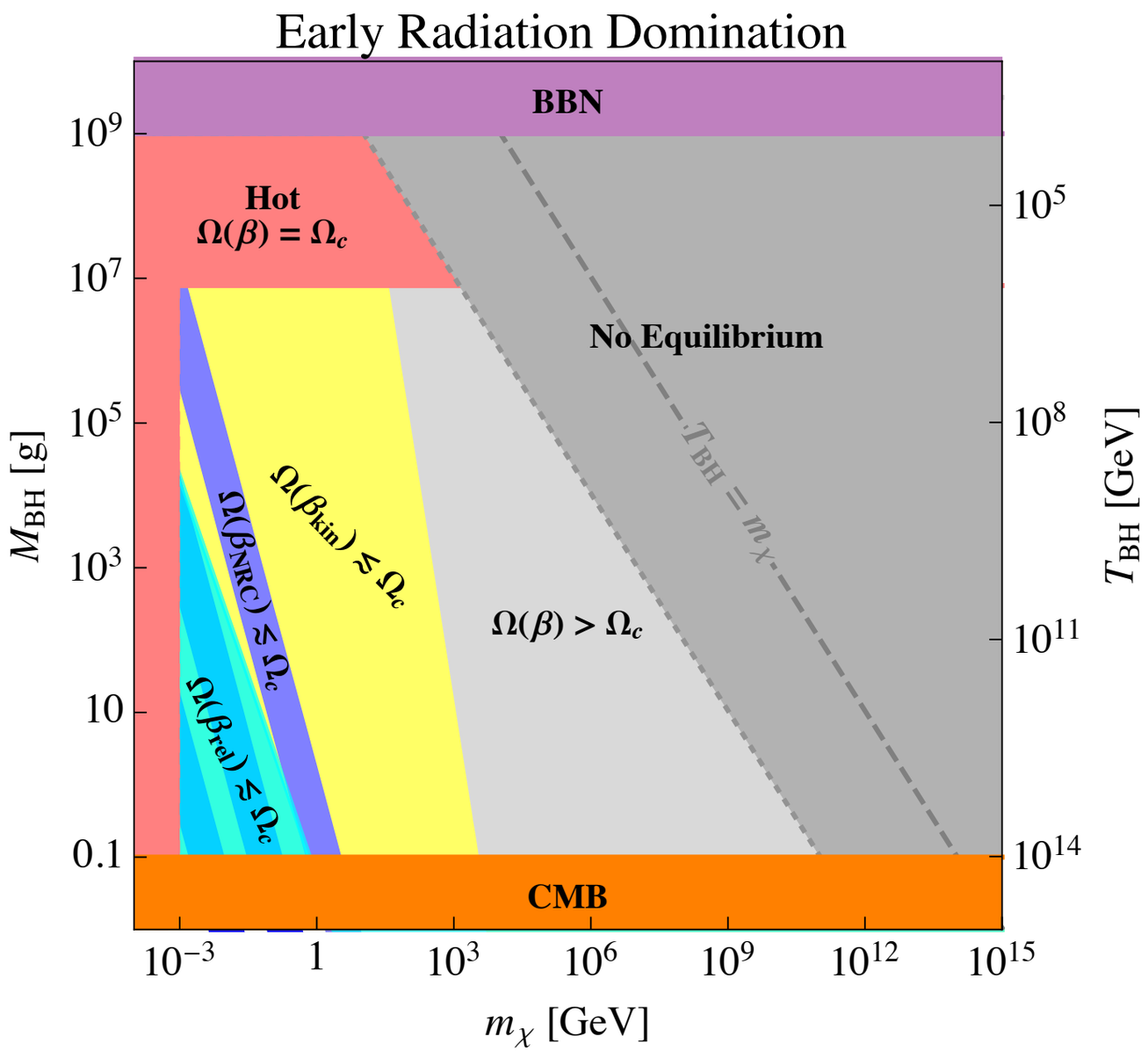


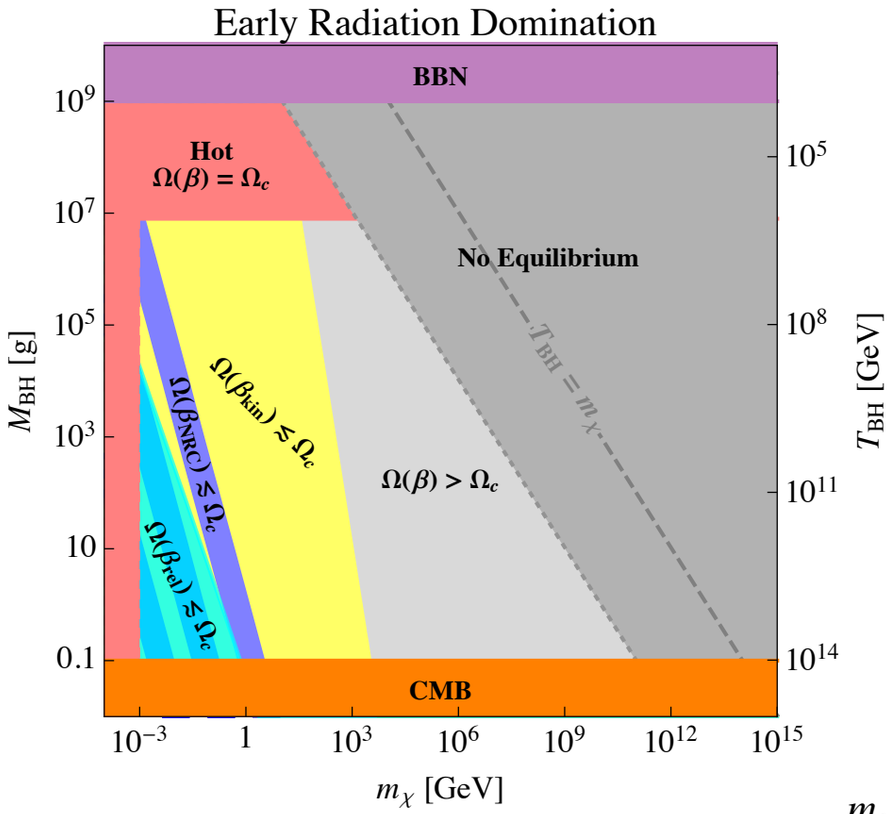
$\beta \geq \beta_{\rm crit}$

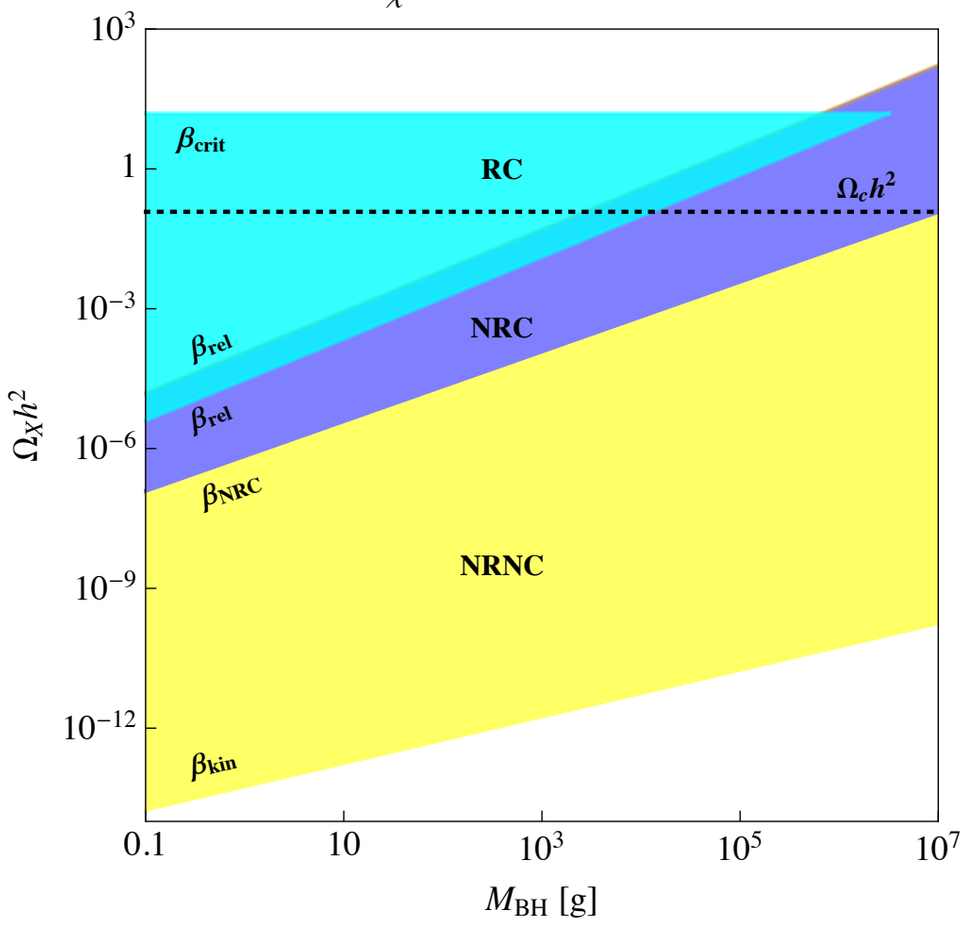
relativistic: cannibalism is inevitable

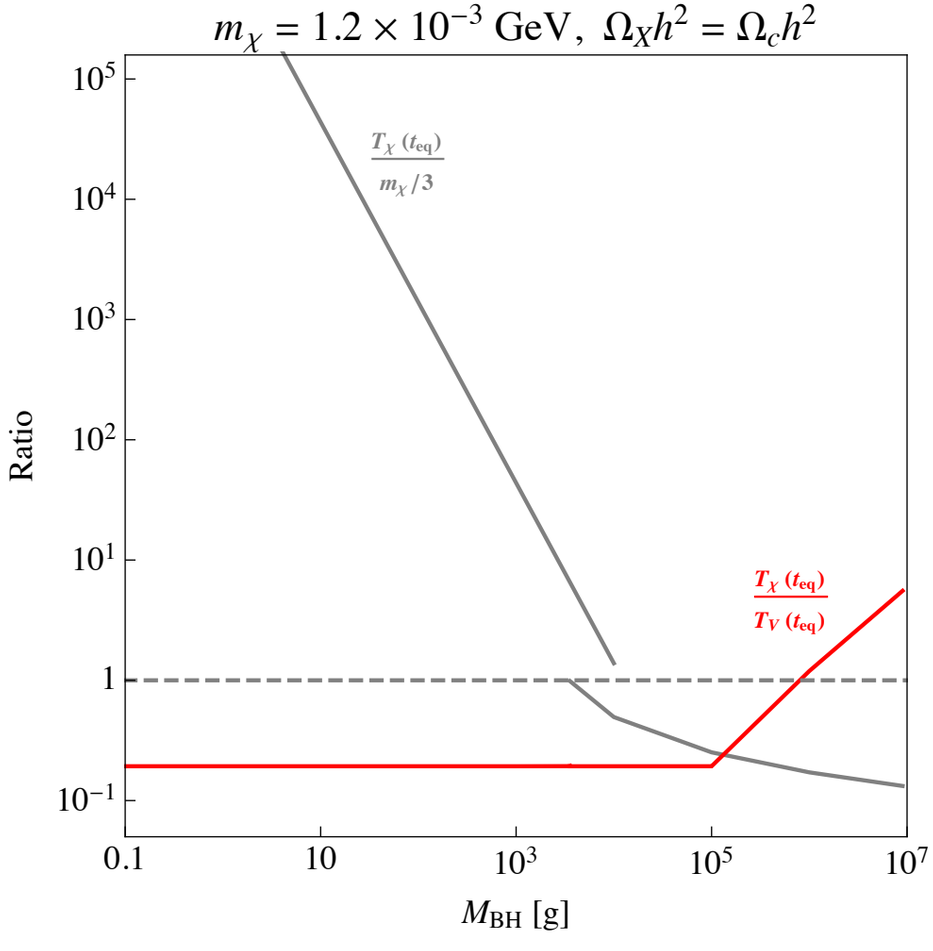
always overproduction of DM

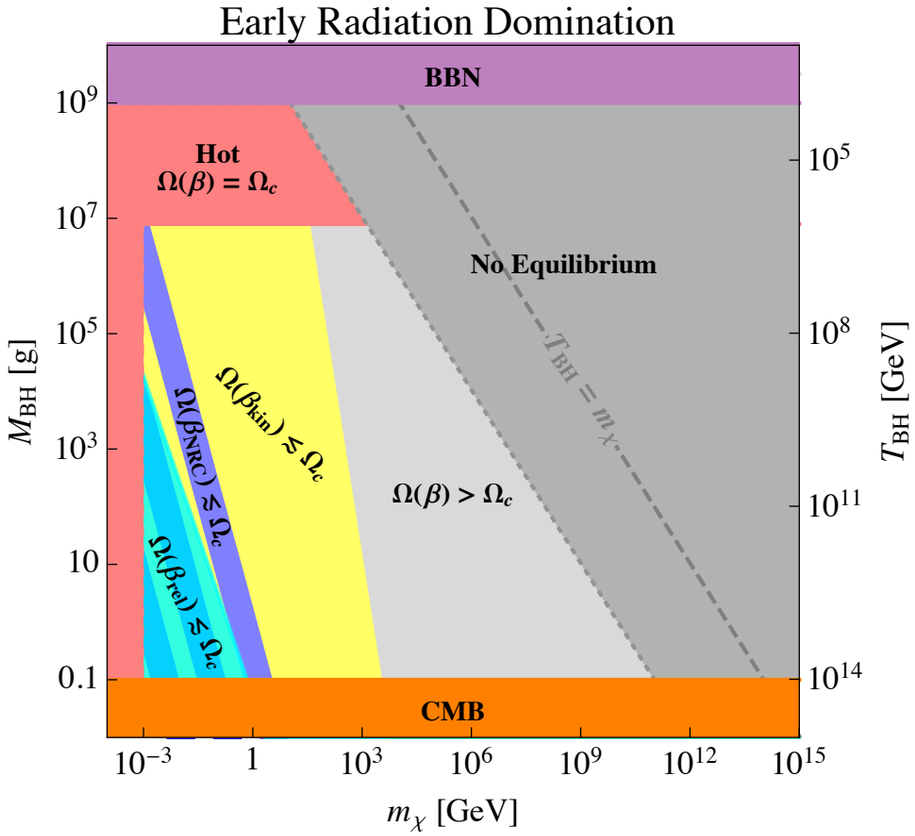
constraints: relic abundance, warm DM




Early Radiation Domination
BBN
Hot
$\Omega(\beta) = \Omega_c$
No Equilibrium
$T_{BH} = m_\chi$
$\Omega(\beta_{kin}) \lesssim \Omega_c$
$\Omega(\beta_{NRC}) \lesssim \Omega_c$
$\Omega(\beta_{rel}) \lesssim \Omega_c$
$\Omega(\beta) > \Omega_c$
CMB
M_{BH} [g]
T_{BH} [GeV]
m_χ [GeV]


$m_\chi = 1.2 \times 10^{-3}$ GeV
β_{crit}
RC
$\Omega_c h^2$
β_{rel}
NRC
β_{rel}
β_{NRC}
NRNC
β_{kin}
$\Omega_X h^2$
M_{BH} [g]


$m_\chi = 1.2 \times 10^{-3}$ GeV, $\Omega_X h^2 = \Omega_c h^2$
$\frac{T_\chi\,(t_{eq})}{m_\chi/3}$
$\frac{T_\chi\,(t_{eq})}{T_V\,(t_{eq})}$
Ratio
M_{BH} [g]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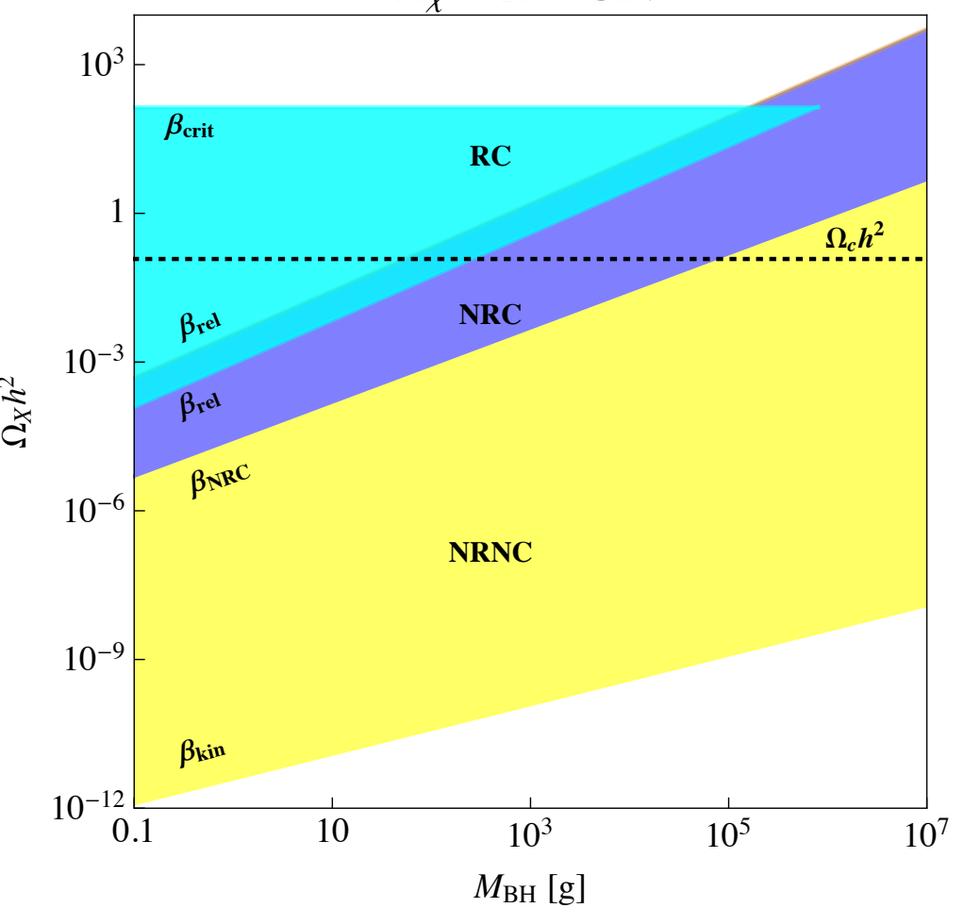
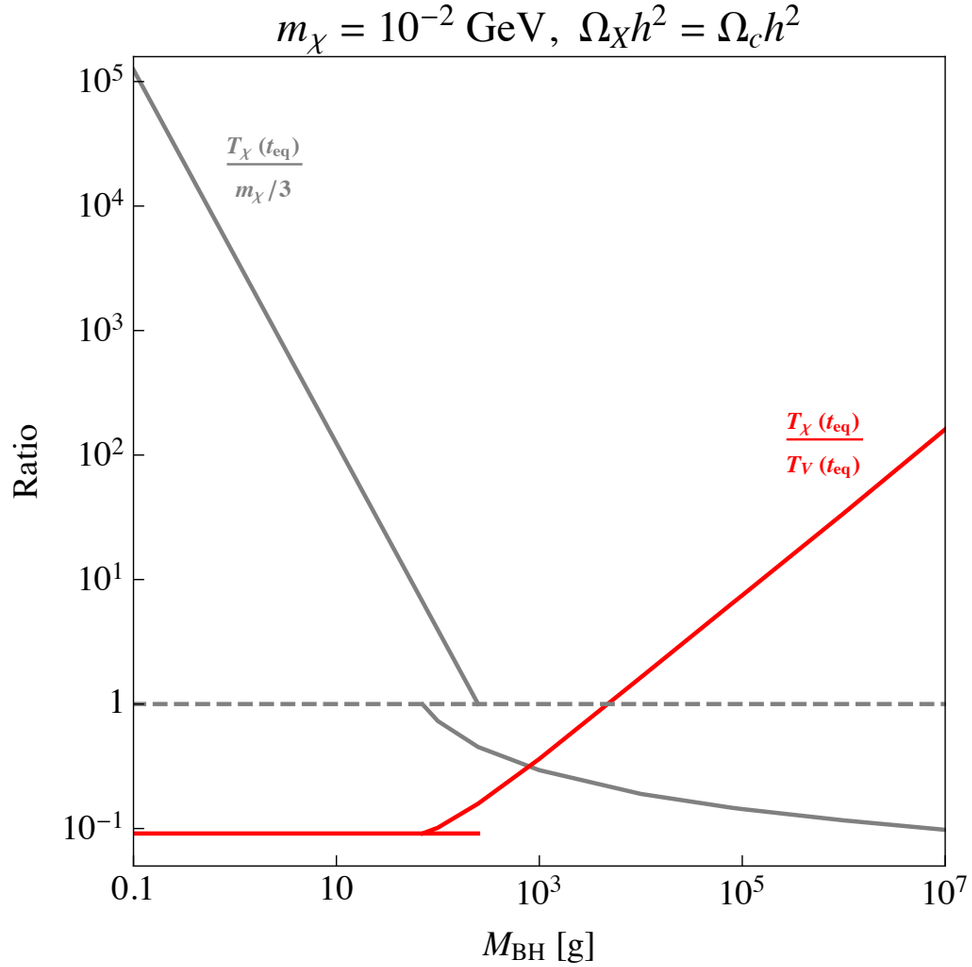
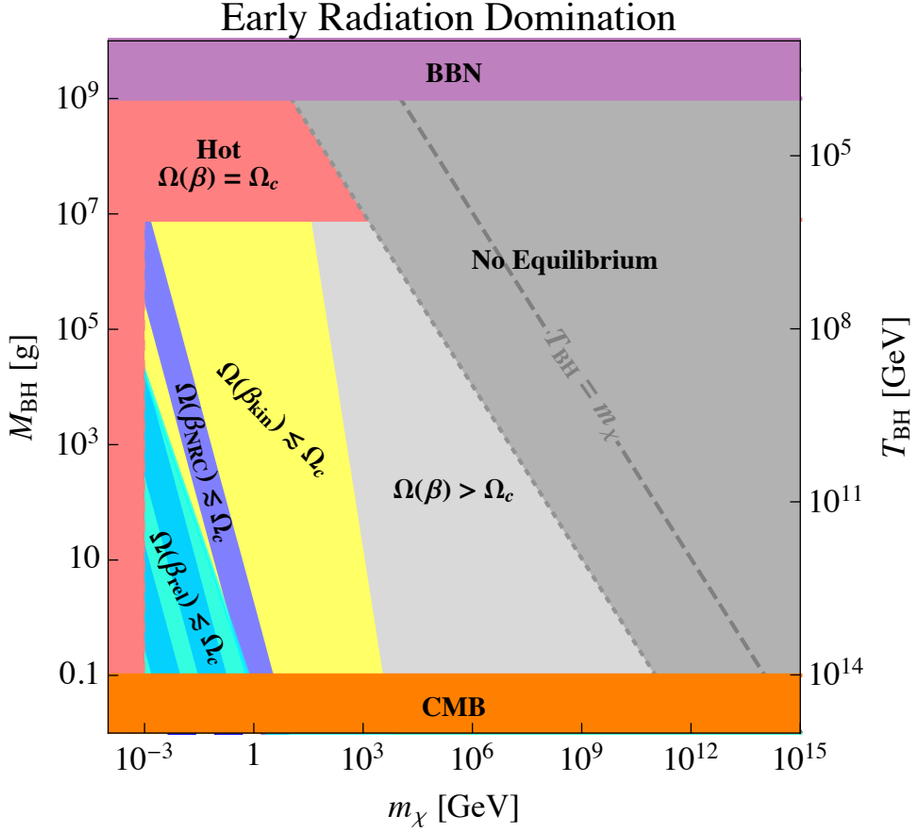
$\Omega(\beta) > \Omega_c$
CMB
M_{BH} [g]
T_{BH} [GeV]
m_χ [GeV]


$m_\chi = 10^{-2}$ GeV
β_{crit}
RC
$\Omega_c h^2$
β_{rel}
NRC
β_{rel}
β_{NRC}
NRNC
β_{kin}
$\Omega_\chi h^2$
M_{BH} [g]


$m_\chi = 10^{-2}$ GeV, $\Omega_\chi h^2 = \Omega_c h^2$
$\frac{T_\chi\,(t_{eq})}{m_\chi/3}$
$\frac{T_\chi\,(t_{eq})}{T_V\,(t_{eq})}$
Ratio
M_{BH} [g]


Early Radiation Domination
BBN
Hot
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$T_{BH} = m_\chi$
$\Omega(\beta_{kin}) \lesssim \Omega_c$
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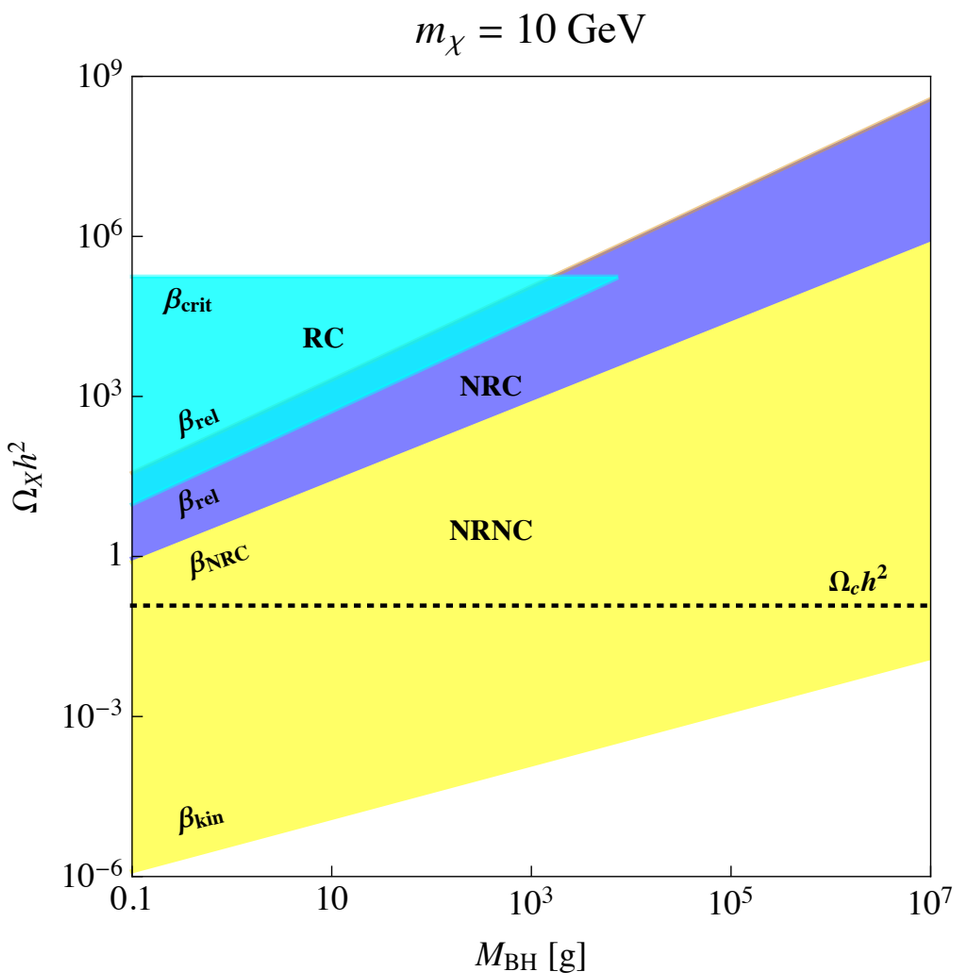
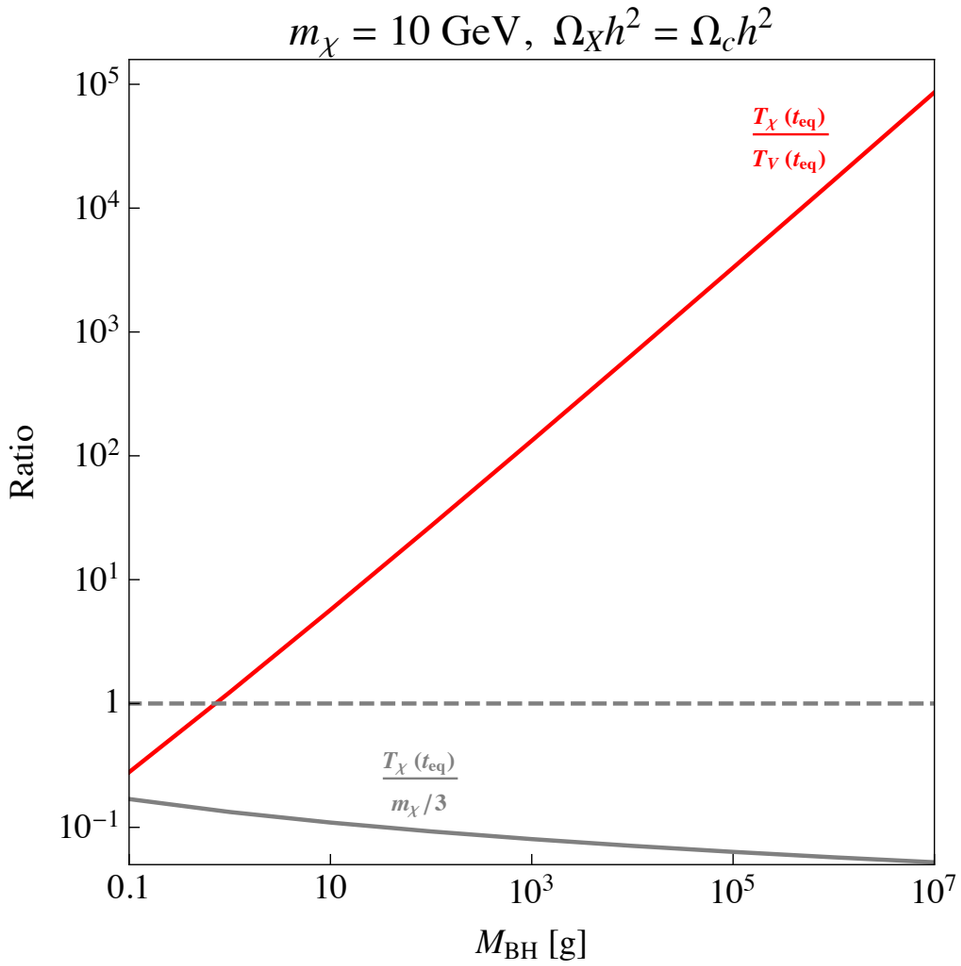
$\Omega(\beta) > \Omega_c$
CMB
M_{BH} [g]
T_{BH} [GeV]
m_χ [GeV]


$m_\chi = 10$ GeV
β_{crit}
RC
β_{rel}
NRC
β_{rel}
β_{NRC}
NRNC
$\Omega_c h^2$
β_{kin}
$\Omega_X h^2$
M_{BH} [g]


$m_\chi = 10$ GeV, $\Omega_X h^2 = \Omega_c h^2$
$\frac{T_\chi(t_{eq})}{T_V(t_{eq})}$
$\frac{T_\chi(t_{eq})}{m_\chi/3}$
Ratio
M_{BH} [g]

Conclusions

- Light PBHs are motivated by many scenarios.

- Hawking evaporation of PBHs can populate a self-interacting dark sector which is hotter or colder than the visible sector.

- The asymmetry in temperatures of the two sectors is persistent.

- DM with right relic abundance points to MeV-TeV mass range.