Asymmetric Reheating by Primordial Black Holes

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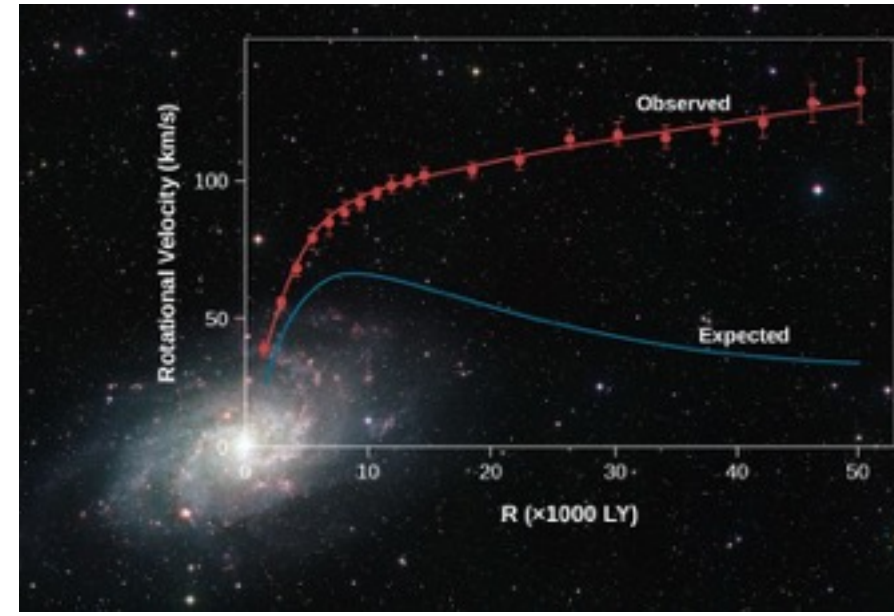
Evidence for DM:
(All from Gravitational Interaction)

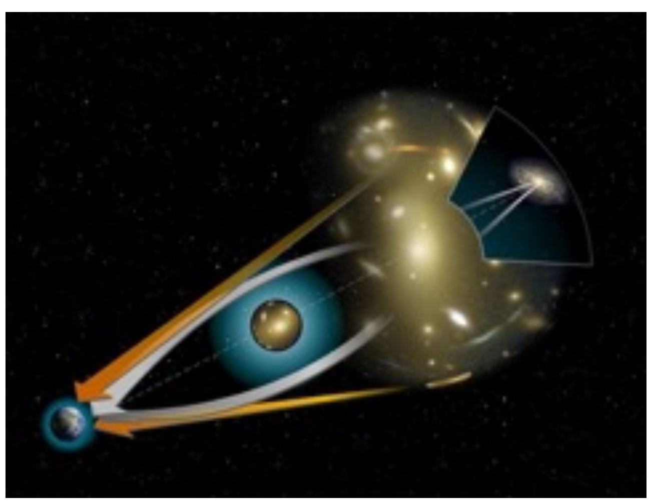


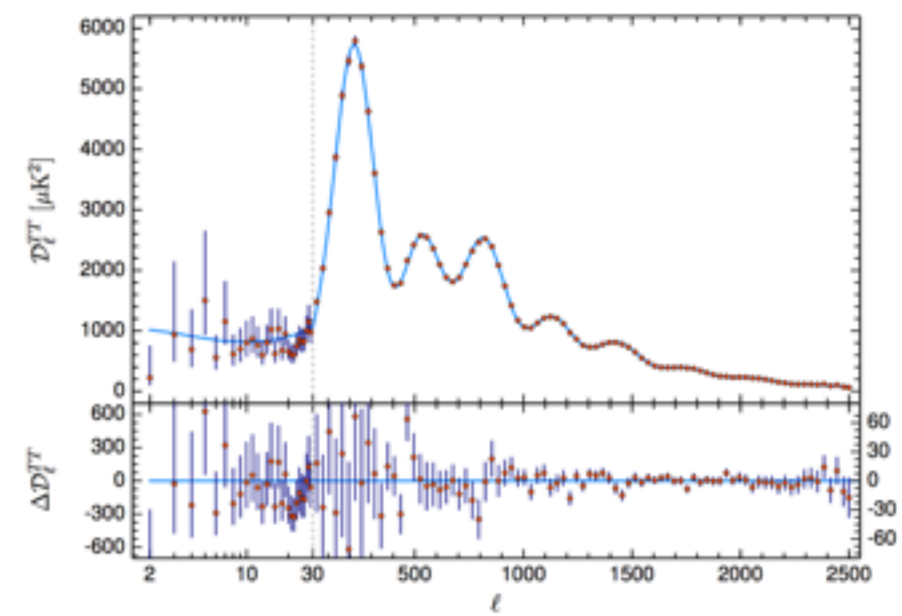
Rotation Curves of Galaxies

Cosmic Microwave Background (CMB)

Structure Formation

Gravitational Lensing

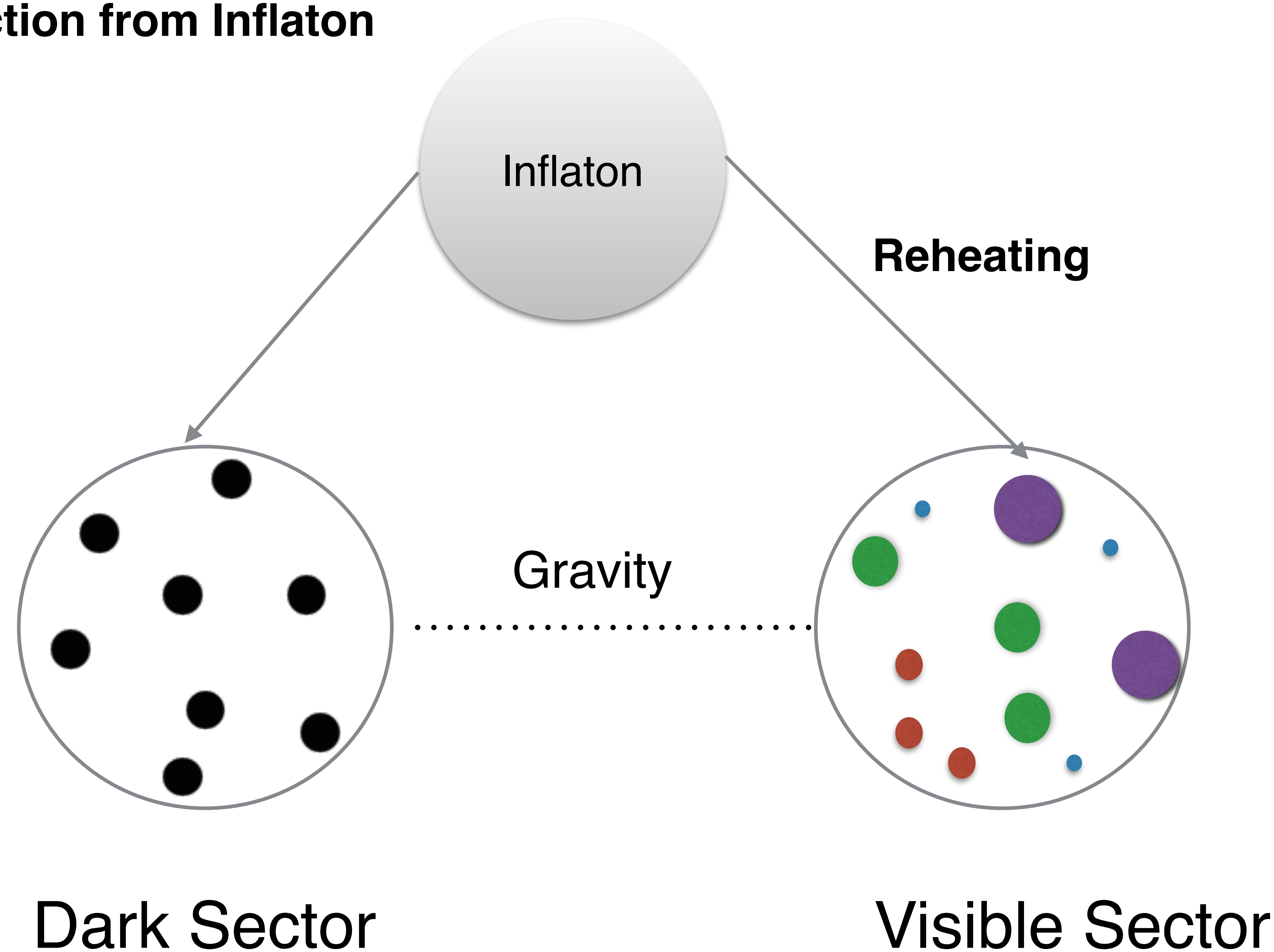




Null result of search for possible non-gravitational interactions of DM: motivates idea of dark sectors coupled only gravitationally to visible sector.

challenge: populating the dark sector

Direct Production from Inflaton



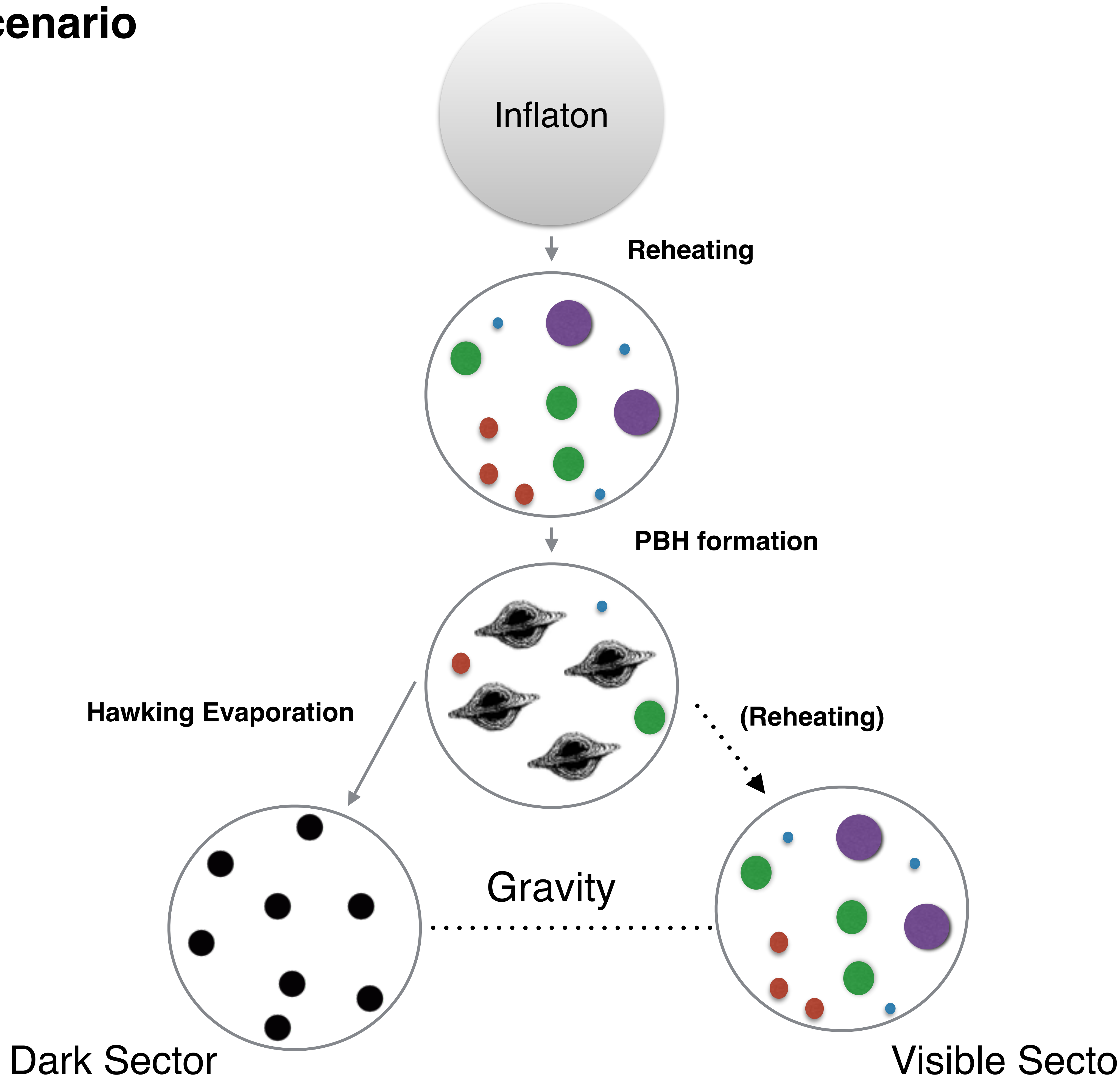
issue: two sectors can exchange inflaton and thermalize

P. Adshead, Y. Cui and J. Shelton, 2016

E. Hardy and J. Unwin, 2017

P. Adshead, P. Raleganker and J. Shelton, 2019

New Scenario



PBHs: Y. B. Zel'dovich, I. D. Novikov, 1967

motivated by many different scenarios

- collapse from inhomogeneities
- sudden reduction in the pressure
- collapse of cosmic loops
- bubble collisions

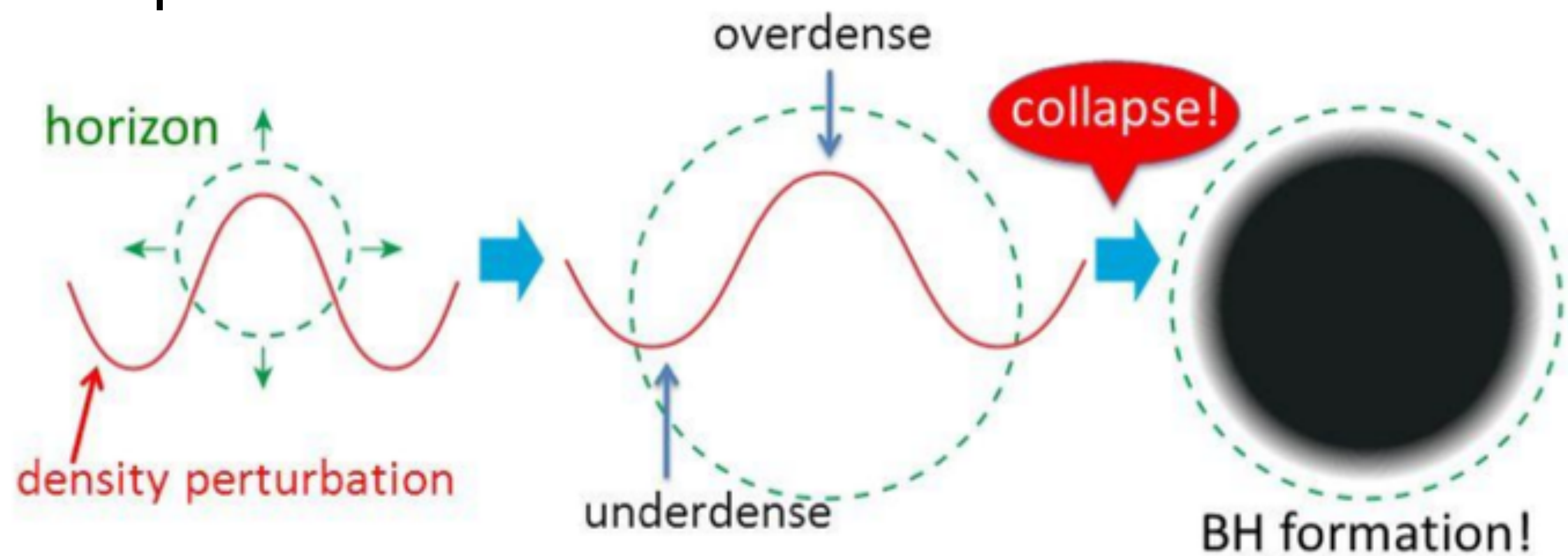


image credit: https://slideplayer.com/slide/7773485/

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

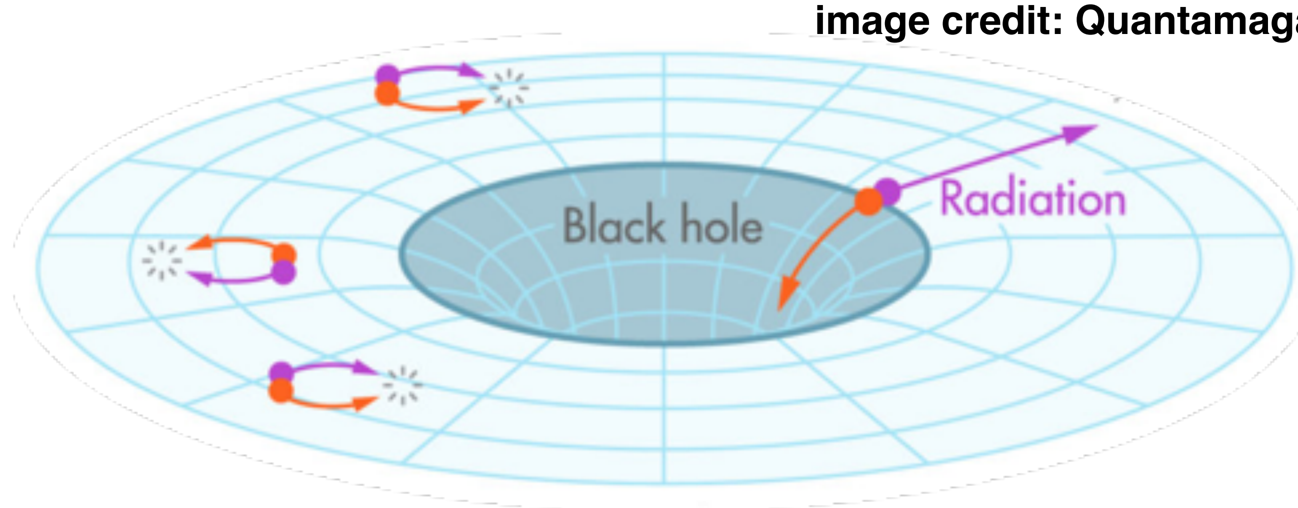
mass: of the order of the horizon mass

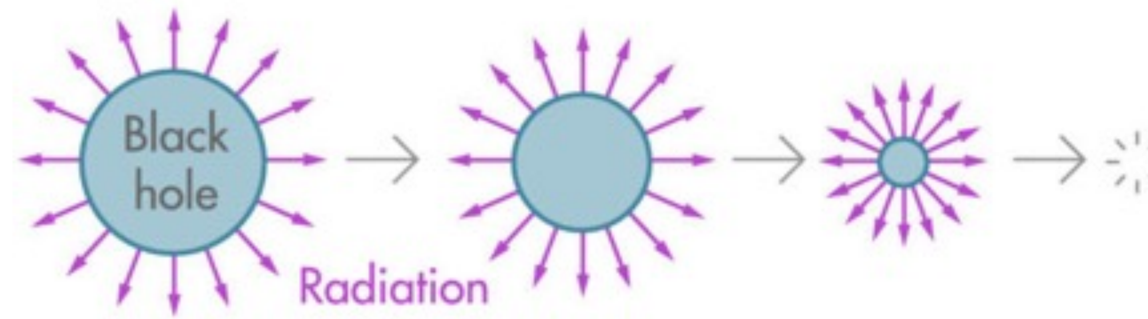
formed in a radiation dominated era:
spin: negligible

Hawking Evaporation:

S. Hawking, 1975

image credit: Quantamagazine





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

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

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

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

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

$$0.1\,{\rm g} \lesssim M_{\rm BH} \lesssim 10^9\,{\rm g}$$

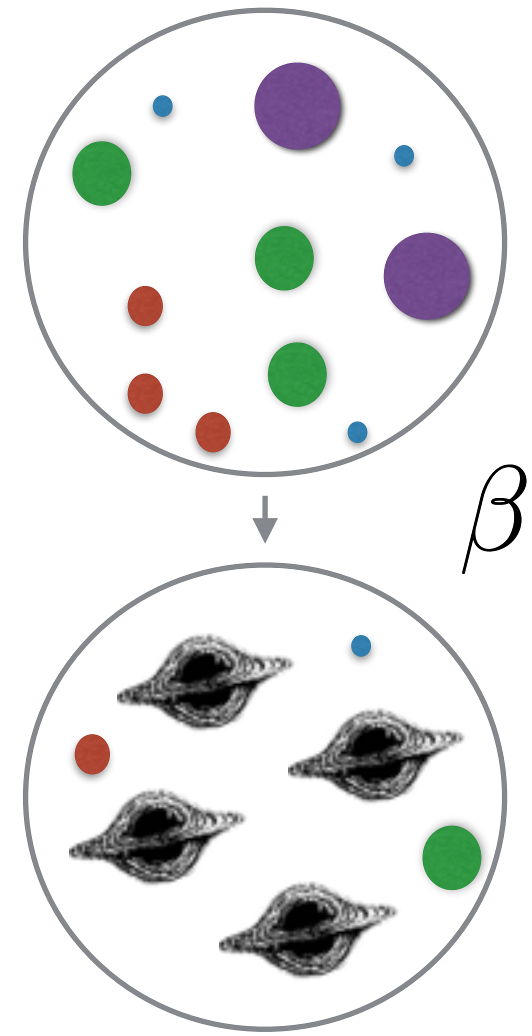
CMB: constraint on the size of Horizon at the end of inflation

$H_I \lesssim 10^{-5} M_{\rm Pl}$ (*Planck*)

evaporate before **BBN**

Not constrained by cosmology

PBH Energy Content:



initial abundance of PBHs $\beta \equiv \frac{\rho_{\rm PBH}(t_i)}{\rho_{\rm rad}(t_i)}$

$$\rho_{\rm PBH} \propto a^{-3}, \quad \rho_{\rm rad} \propto a^{-4}$$

$$\rho_{\rm PBH}(t_{\text{early-eq}})/\rho_{\rm rad}(t_{\text{early-eq}}) \sim 1 \qquad t_{\text{early-eq}} \lesssim t_{\rm eva}$$

an initially radiation-dominated universe will eventually become matter-dominated if the PBHs are still around.

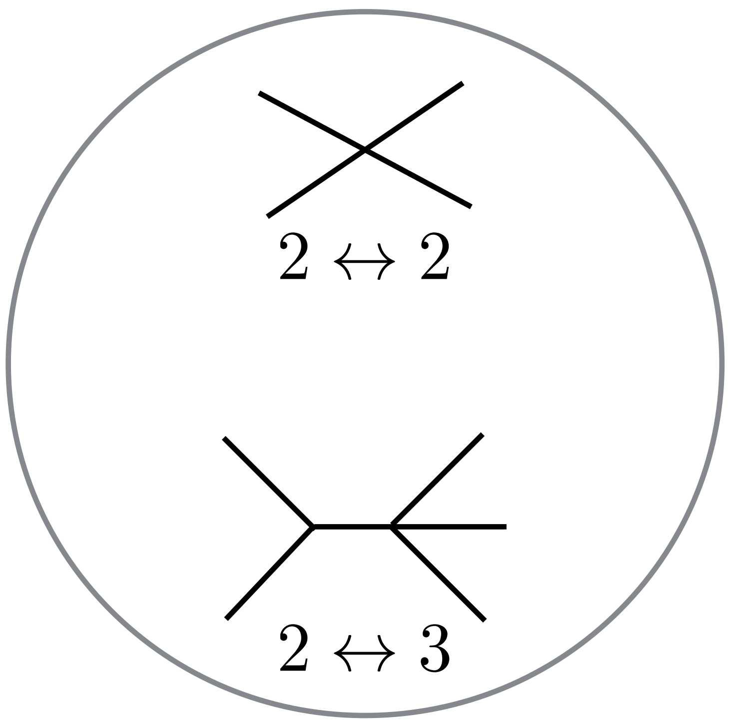
critical initial abundance $\beta_{\rm crit} \sim \frac{M_{\rm Pl}}{M_{\rm BH}}$

$\beta < \beta_{\rm crit}$ evaporation happens in a RD Universe

$\beta \geq \beta_{\rm crit}$ evaporation happens in a MD Universe

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

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



Dark Sector

$t = \tau : n_\chi(\tau), \rho_\chi(\tau)$ populating $(\lambda \simeq 1)$

$2 \leftrightarrow 2$ kinetic equilibrium: leads to a temperature and non-zero chemical potential

$$\frac{\Gamma_{\chi,2\to 2}(t)}{H(t)} \sim \frac{n_\chi(t)/\bar{E}_\chi(t)^2}{H(t)} \propto a(t), \qquad \tau \lesssim t \lesssim t_m$$

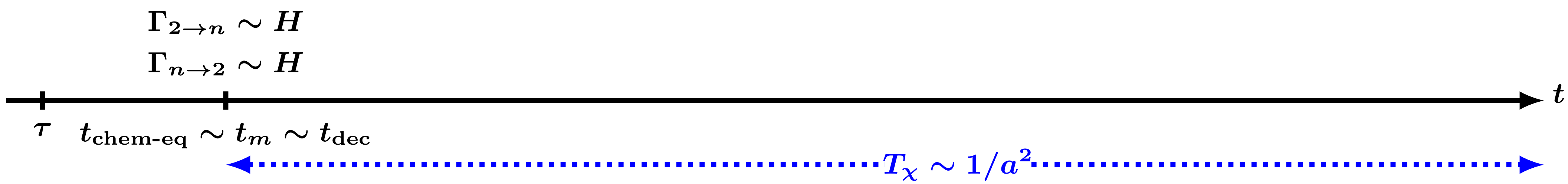
$2 \to 3$ Chemical equilibrium: gives rise to a temperature and zero chemical potential

$$\frac{\Gamma_{\chi,2\to 3}(t)}{H(t)} \sim \frac{n_\chi(t)m_\chi^2/T_\chi^4(t)}{H(t)} \propto a^3(t), \qquad t_{\text{kin-eq}} \lesssim t \lesssim t_m$$

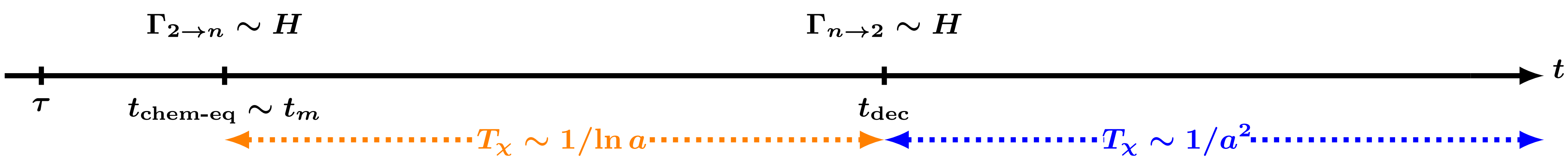
$3 \to 2$ Cannibalism/decoupling (freeze-out):

$$\frac{\Gamma_{\chi,3\to 2}(t)}{H(t)} \sim \frac{n_\chi^2(t)/m_\chi^5}{H(t)}, \qquad t_m \lesssim t \lesssim t_{\text{dec}}$$

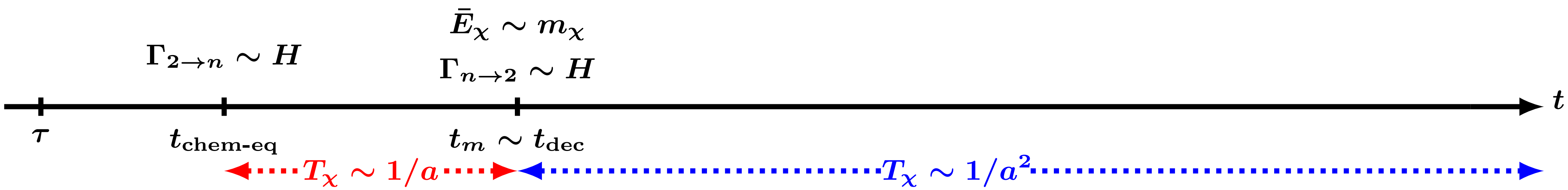
non-relativistic, no cannibalism (NRNC):



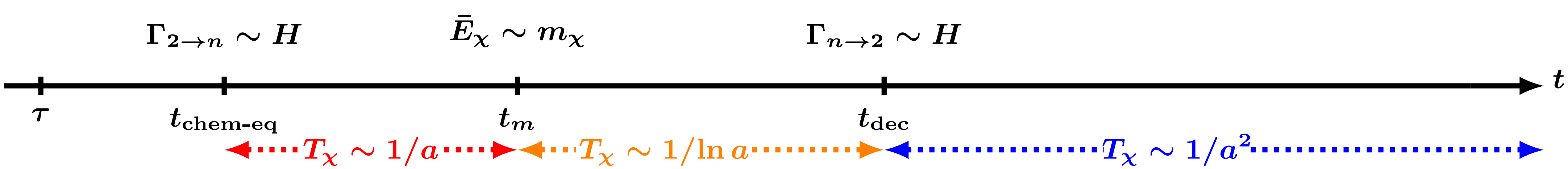
non-relativistic, with cannibalism (NRC):



relativistic, no cannibalism (RNC):



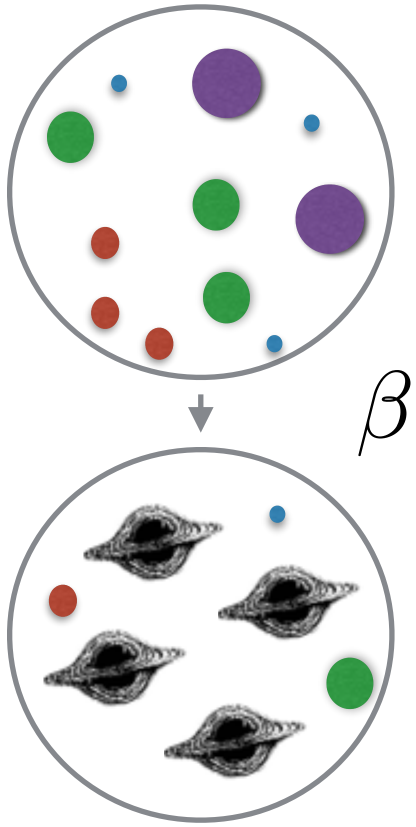
relativistic, with cannibalism (RC):



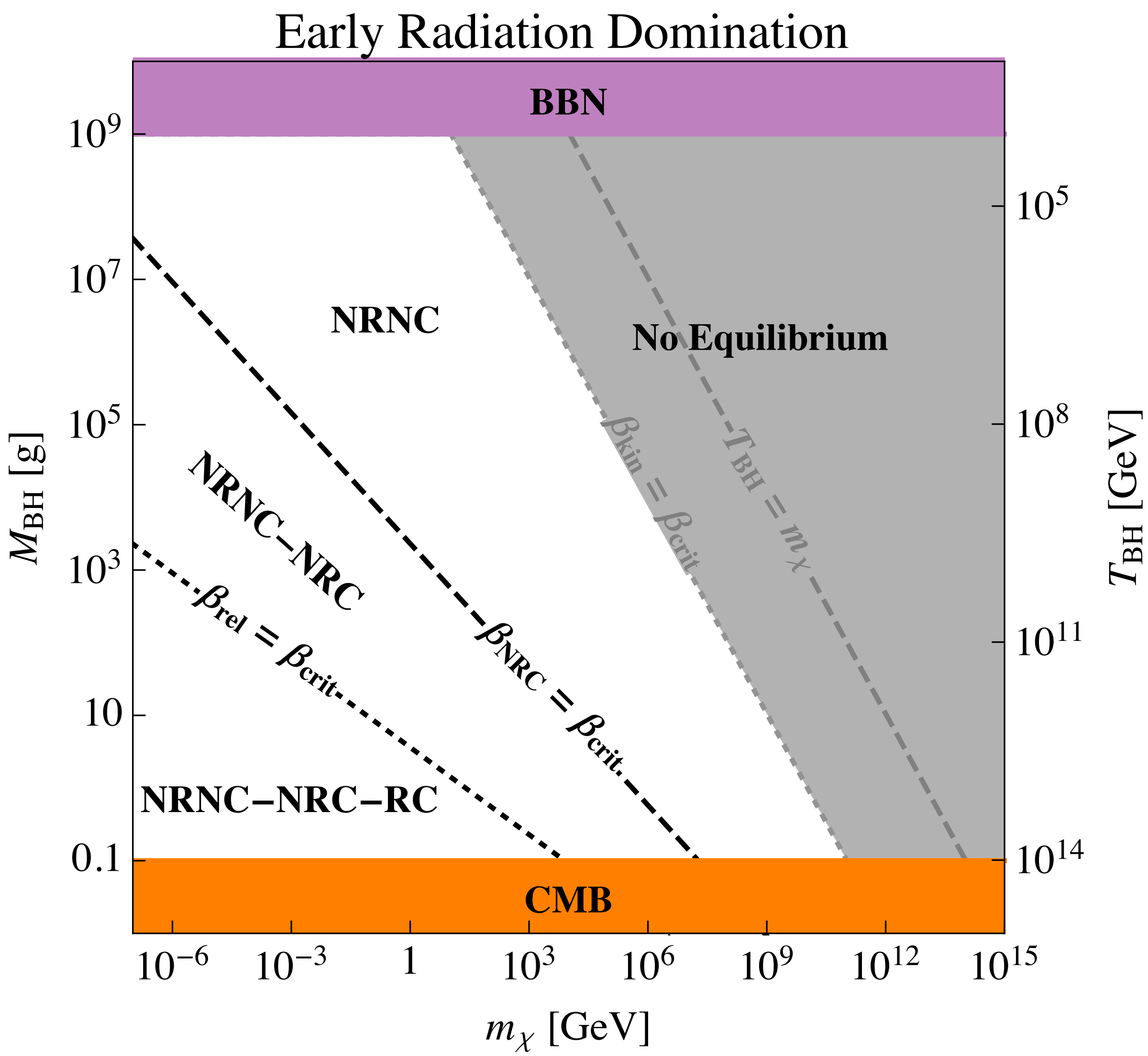
Populating a self-interacting dark sector by Hawking evaporation of PBHs:

$$\beta \equiv \frac{\rho_{\rm PBH}(t_i)}{\rho_{\rm rad}(t_i)}$$

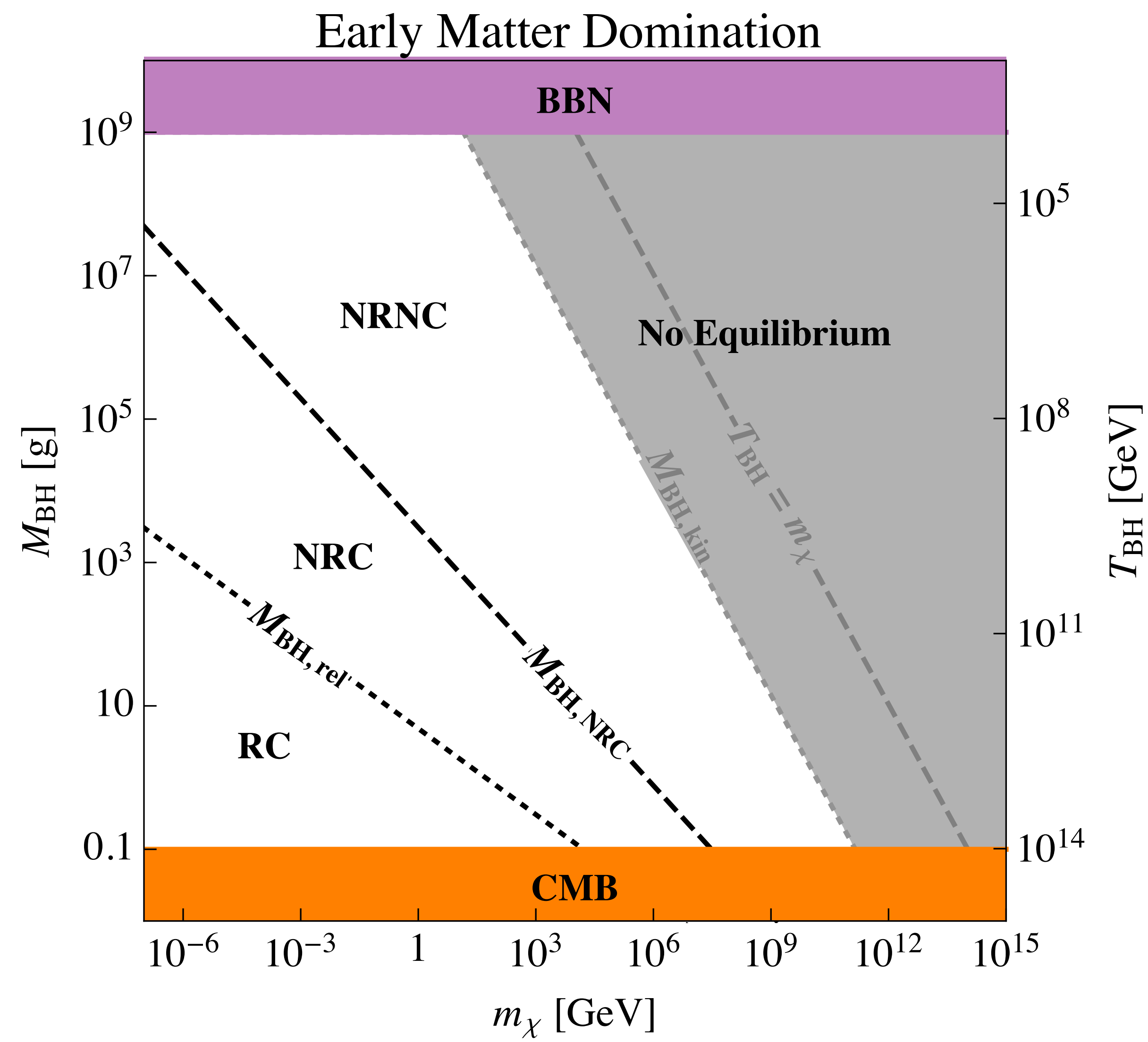
$$\beta_{\rm crit} \sim \frac{M_{\rm Pl}}{M_{\rm BH}}$$



Thermal History	Early Radiation Domination	Early Matter Domination
NRNC (non-relativistic, no cannibalism)	$\beta_{\rm kin} \lesssim \beta \lesssim \beta_{\rm NRC}$	$M_{\rm BH,\ NRC} \lesssim M_{\rm BH} \lesssim M_{\rm BH,\ kin}$
NRC (non-relativistic, cannibalism)	$\beta_{\rm NRC} \lesssim \beta \lesssim \beta_{\rm rel}$	$M_{\rm BH,\ rel} \lesssim M_{\rm BH} \lesssim M_{\rm BH,\ NRC}$
RNC (relativistic, no cannibalism)	$\beta_{\rm rel} \lesssim \beta \lesssim \beta_{\rm RC}$	$M_{\rm BH,\ RC} \lesssim M_{\rm BH} \lesssim M_{\rm BH,\ rel}$
RC (relativistic, cannibalism)	$\beta_{\rm RC} \lesssim \beta \lesssim \beta_{\rm crit}$	$M_{\rm BH} \lesssim M_{\rm BH,\ RC}$



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

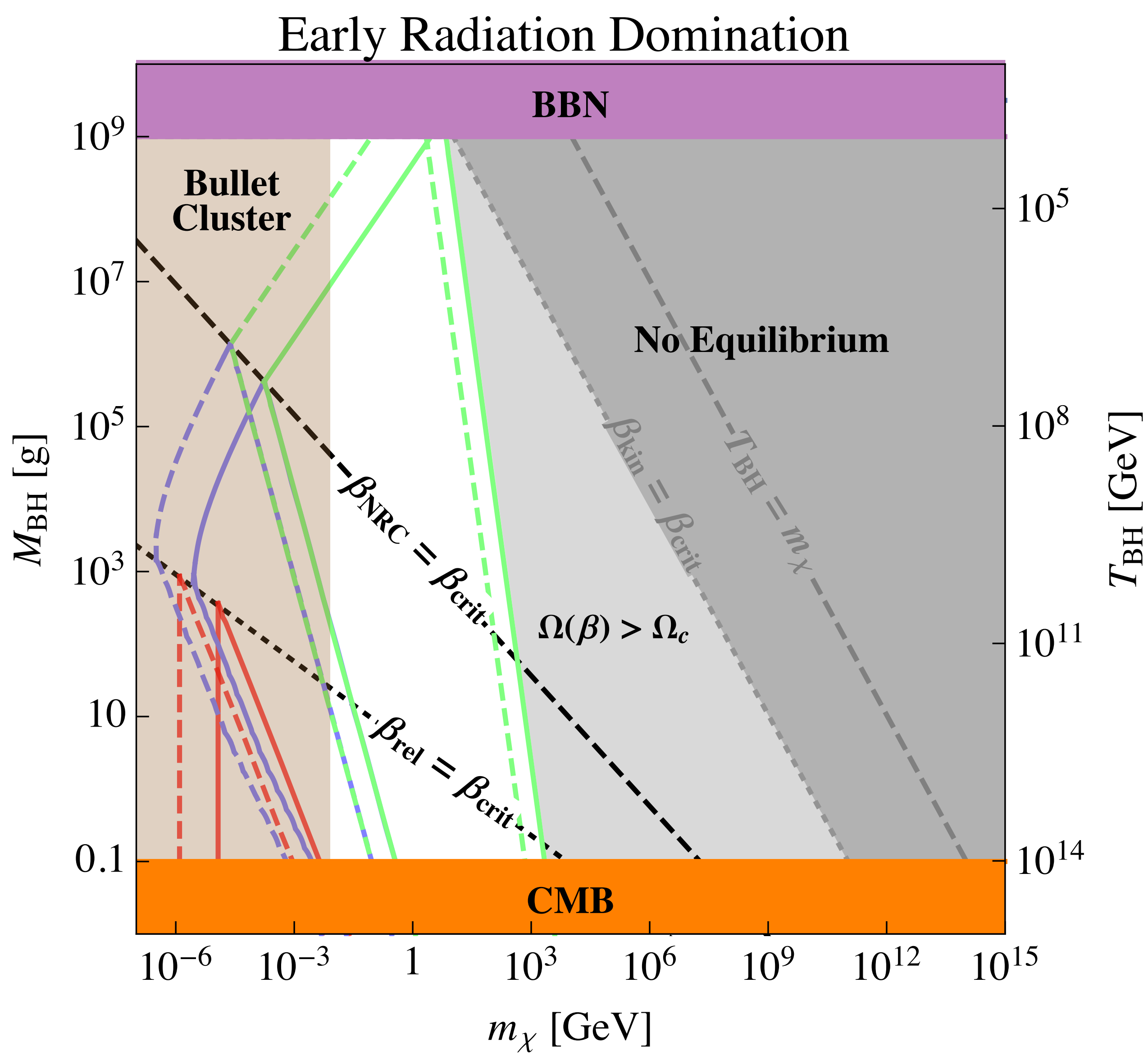


$\beta \geq \beta_{\rm crit}$

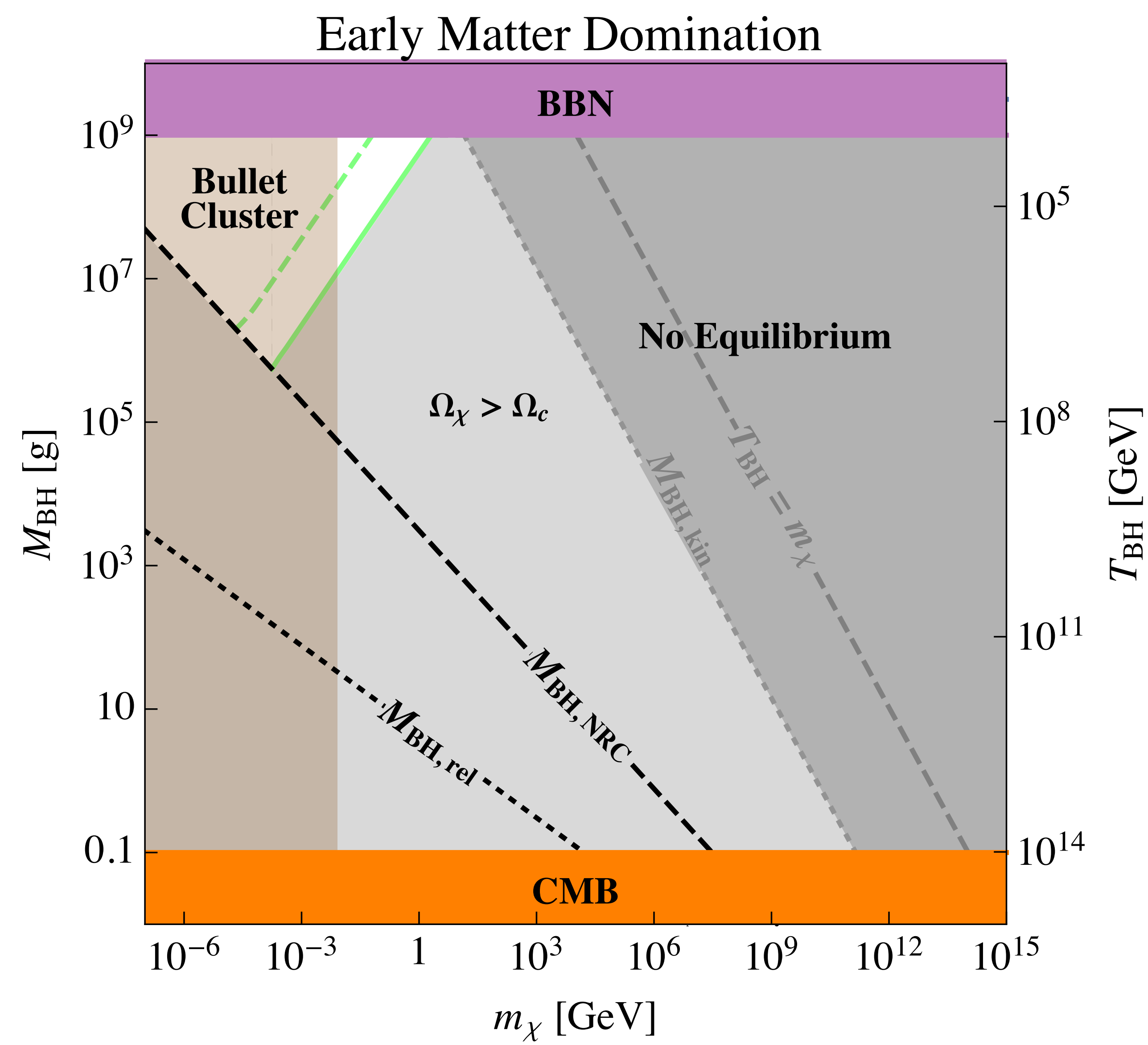
$T_{\rm BH} < m_\chi$ no equilibrium

relativistic: cannibalism is inevitable

Constraints: relic abundance, Bullet Cluster



$\beta < \beta_{crit}$

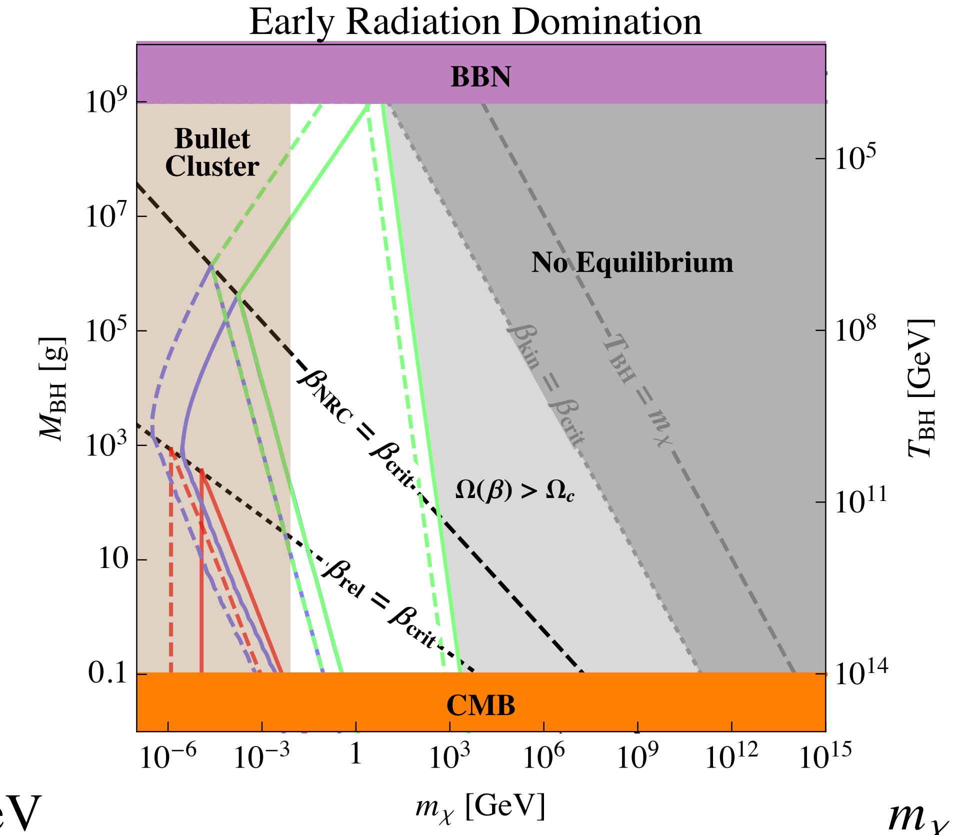


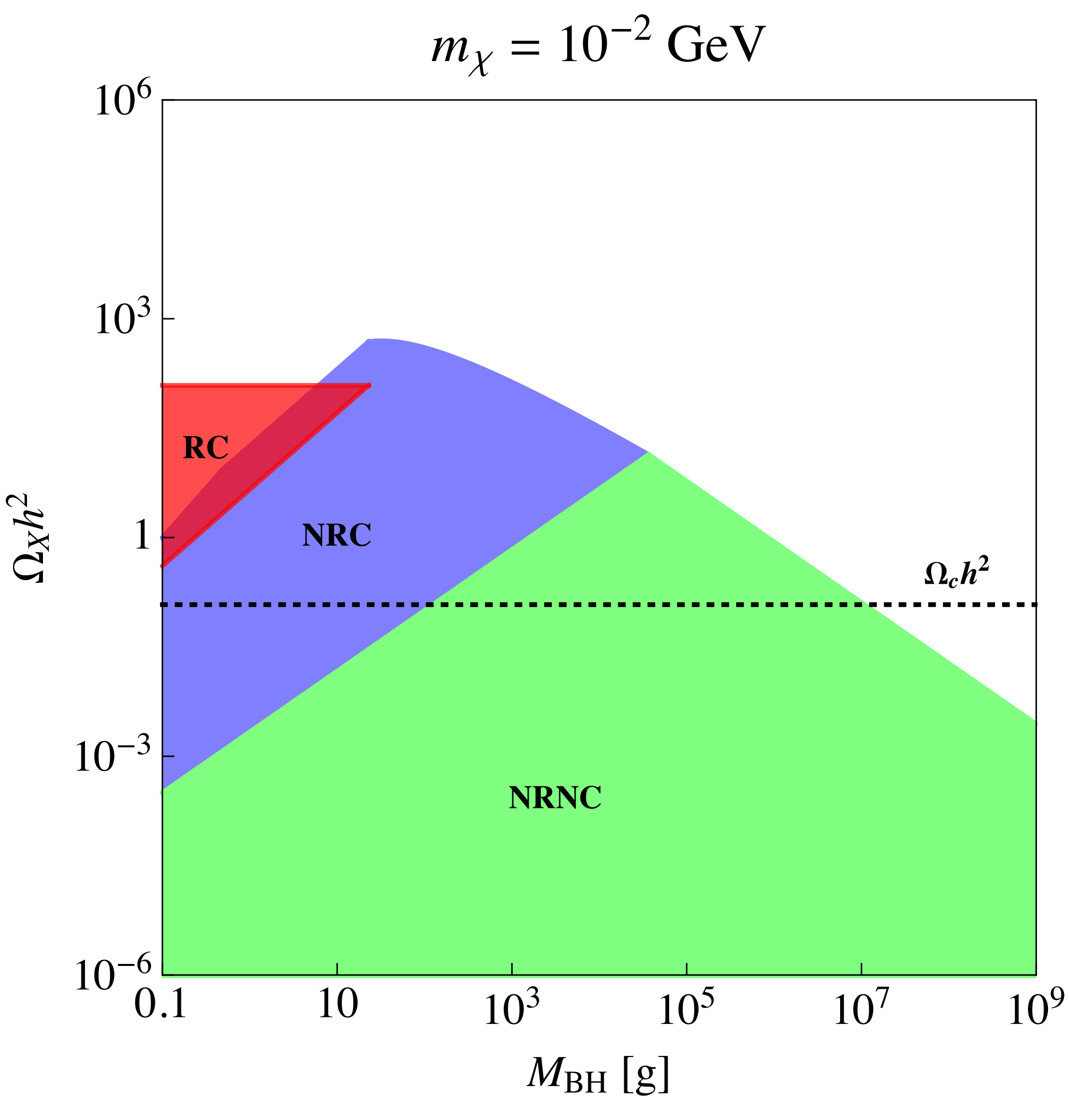
$\beta \geq \beta_{crit}$

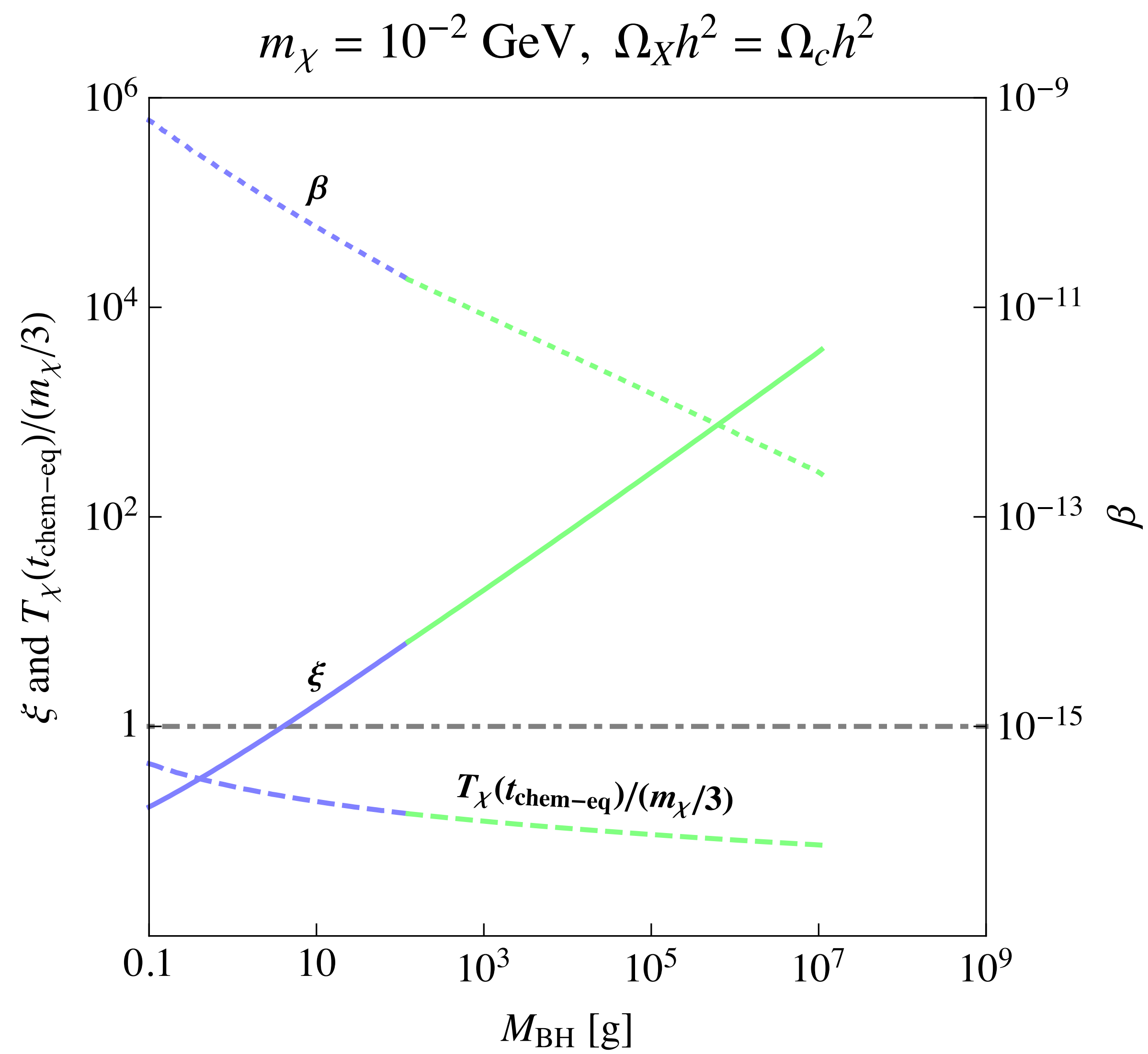
NRNC

NRC

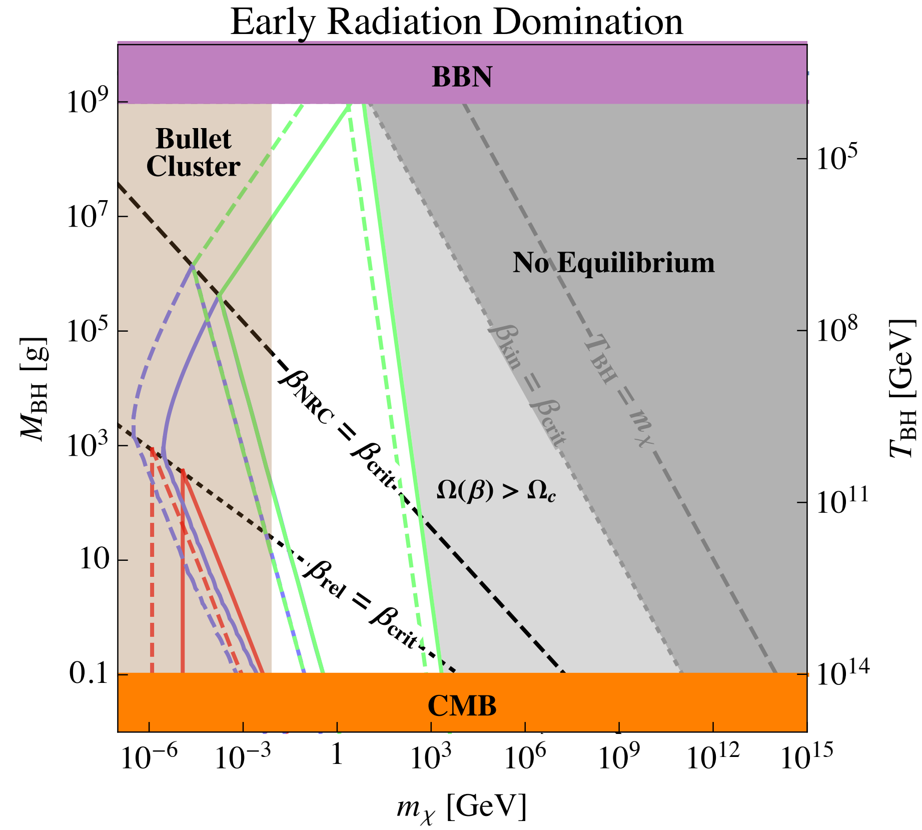
RC

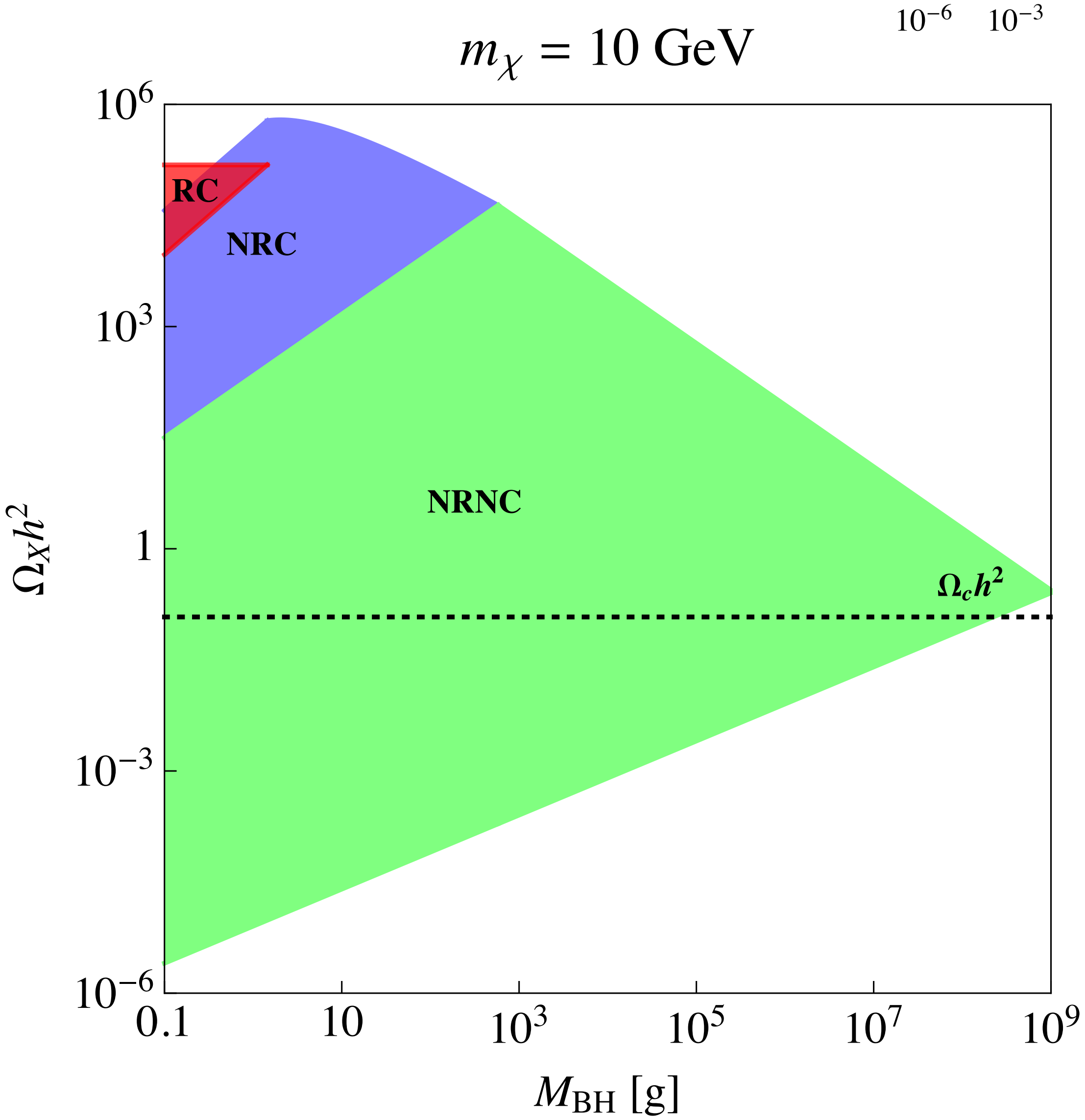


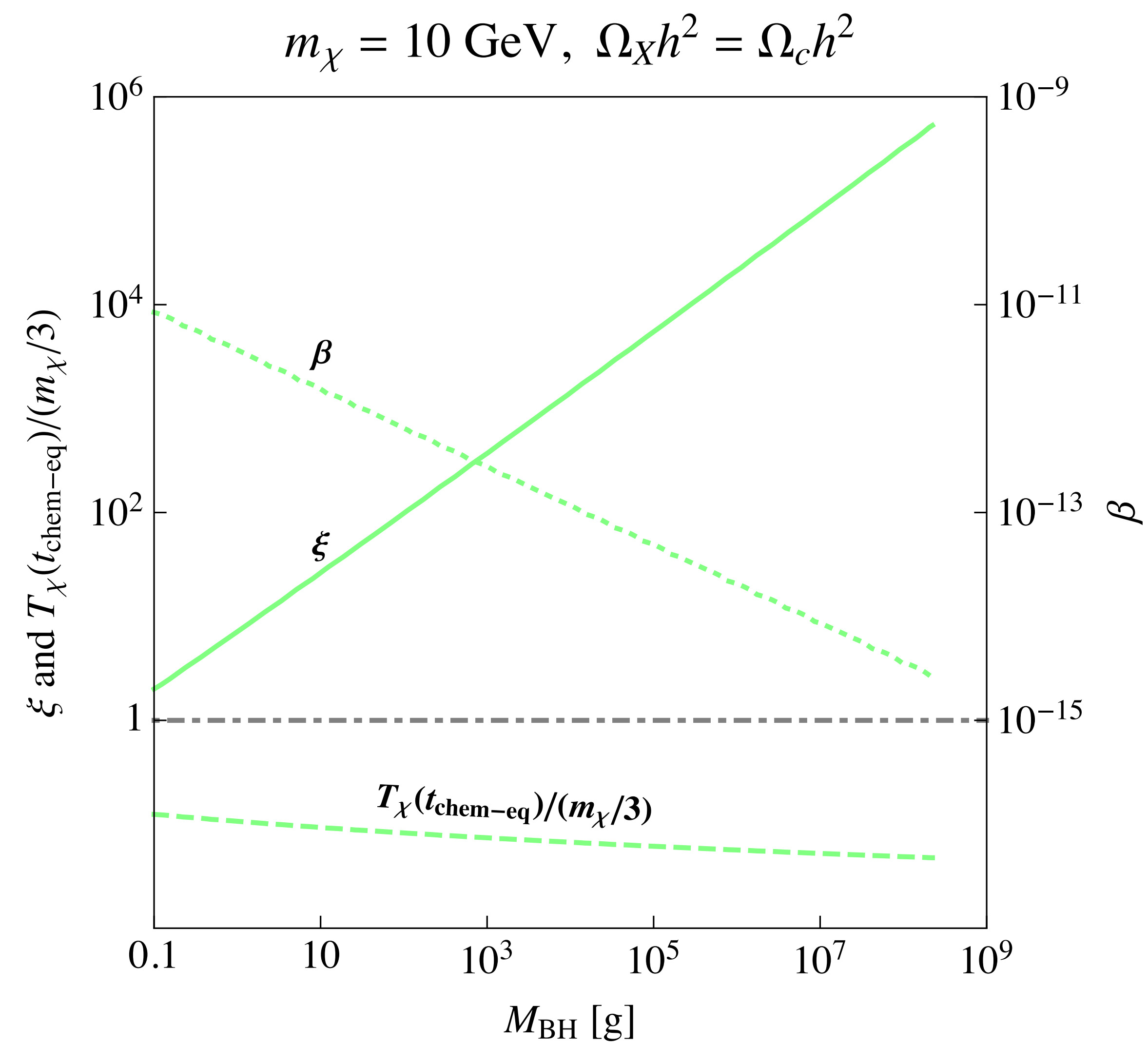




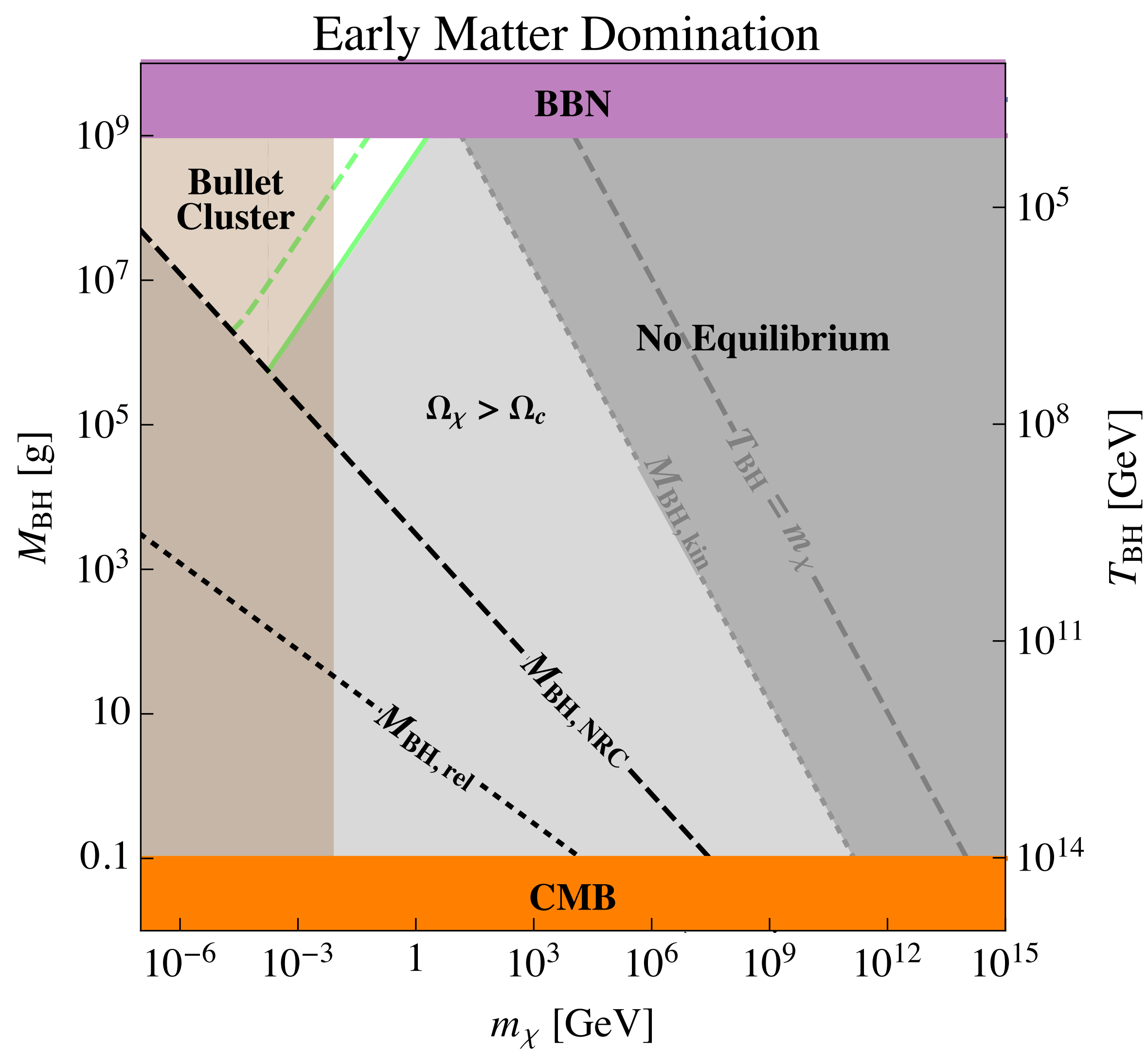
$$\xi = \frac{T_\chi(t_{\rm chem-eq})}{T_V(t_{\rm chem-eq})}$$







$$\xi = \frac{T_\chi(t_{\rm chem-eq})}{T_V(t_{\rm chem-eq})}$$



$$(m_\chi = 8\,\mathrm{MeV}, M_{\mathrm{BH}} = 1.2 \times 10^7\,\mathrm{g}, \xi = 3.3 \times 10^3)$$

$$(m_\chi = 2.1\,\mathrm{GeV}, M_{\mathrm{BH}} = 10^9\,\mathrm{g}, \xi = 5.4 \times 10^5)$$

$$\xi = \frac{T_\chi(t_{\mathrm{chem-eq}})}{T_V(t_{\mathrm{chem-eq}})}$$

Early radiation-dominated Universe:

the NRNC and NRC thermal histories can accommodate ξ less than, equal to, or greater than one.

For RC thermal histories, on the other hand, only $\xi < 1$ is allowed.

Early matter (PBH)-dominated Universe:

an NRNC or NRC thermal history forces $\xi > 1$, while an RC thermal history forces $\xi = 1$.

$$\xi = \frac{T_\chi(t_{\mathrm{chem-eq}})}{T_V(t_{\mathrm{chem-eq}})}$$

Conclusions

- 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.