

# Asymmetric Reheating by Primordial Black Holes

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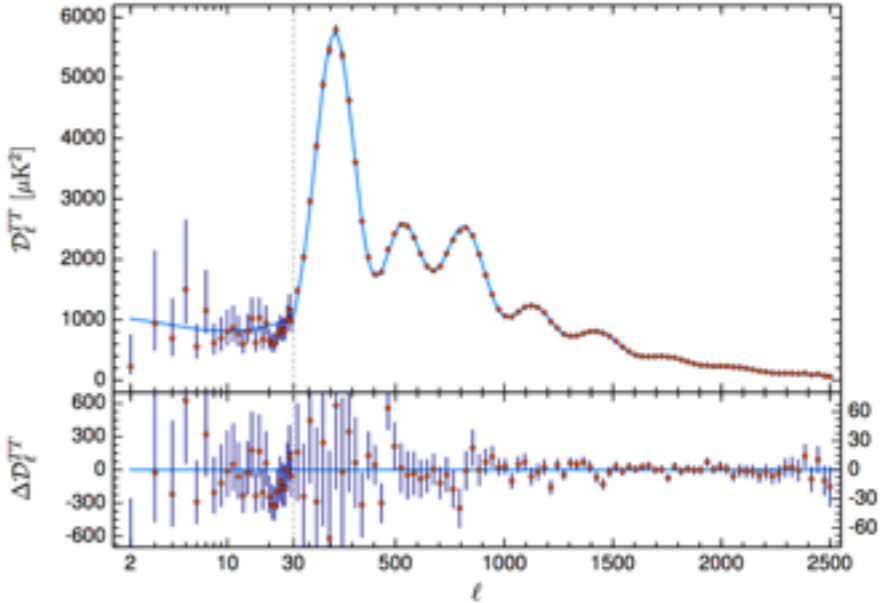
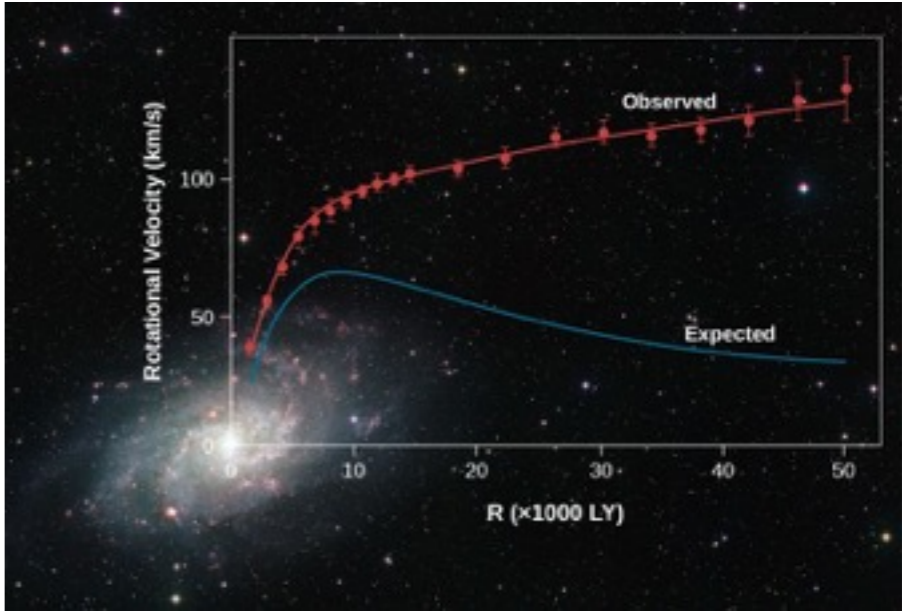
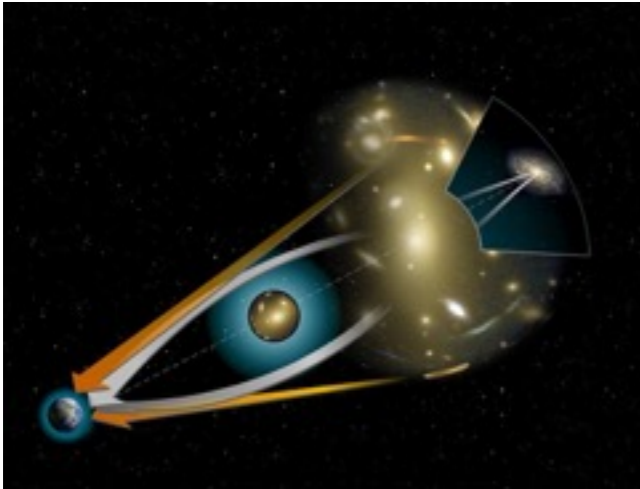
# Evidence for DM: (All from Gravitational Interaction)

Rotation Curves of Galaxies

Cosmic Microwave Background (CMB)

Structure Formation

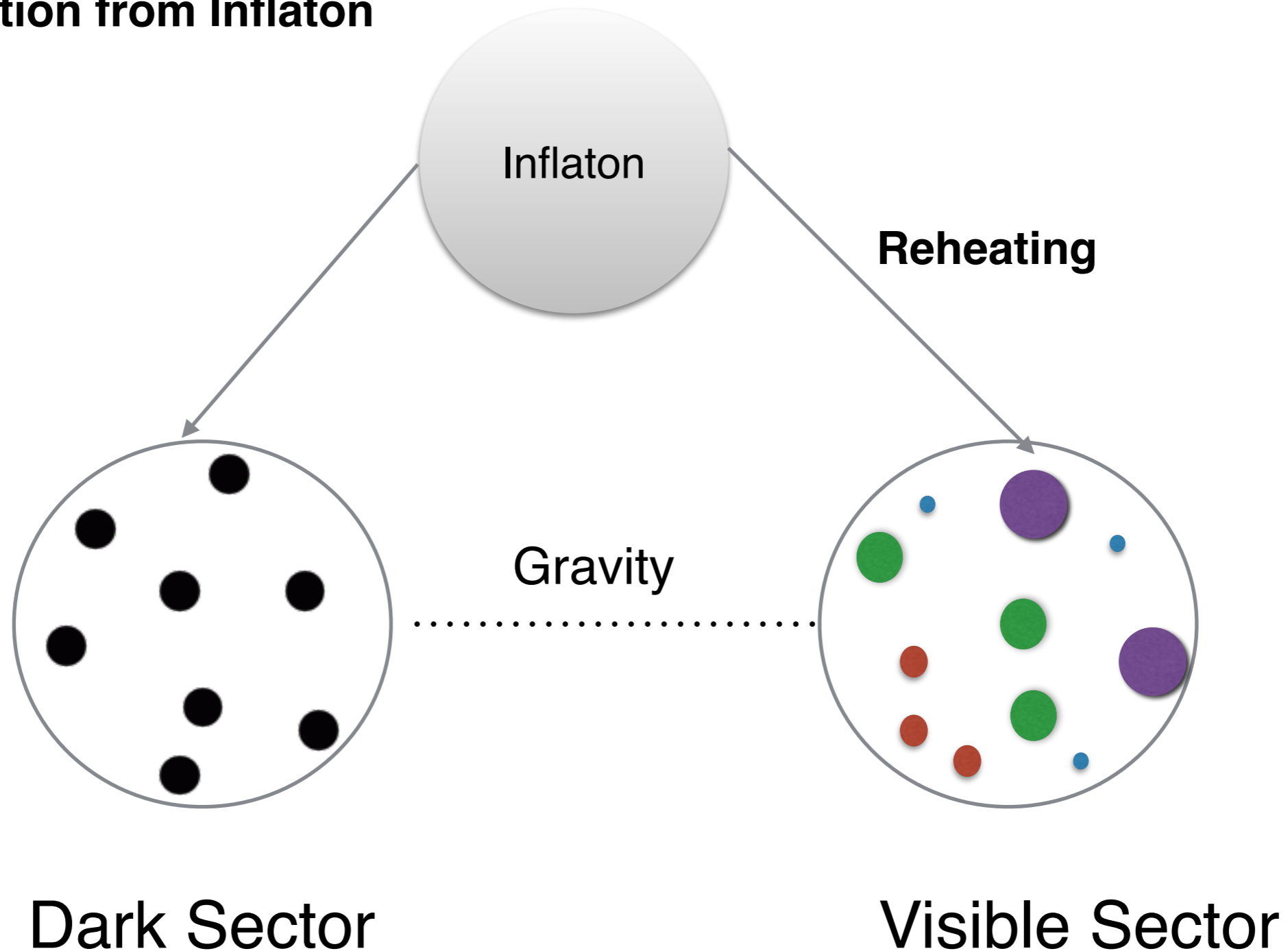
Gravitational Lensing



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



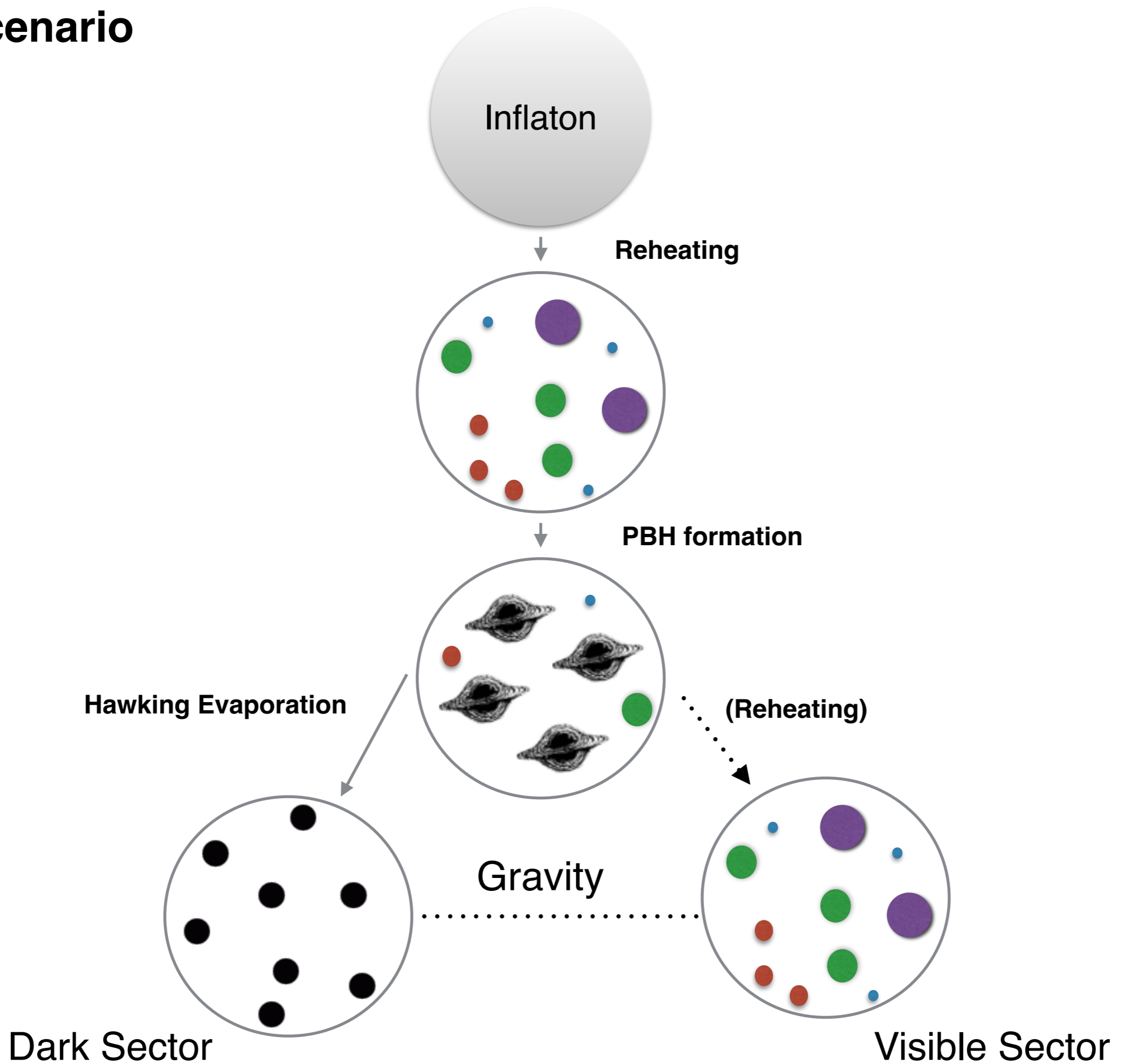
issue: two sectors can exchange inflaton and thermalize

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

E. Hardy and J. Unwin, 2017

P. Adshead, P. Ralegankar and J. Shelton, 2019 2

# 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

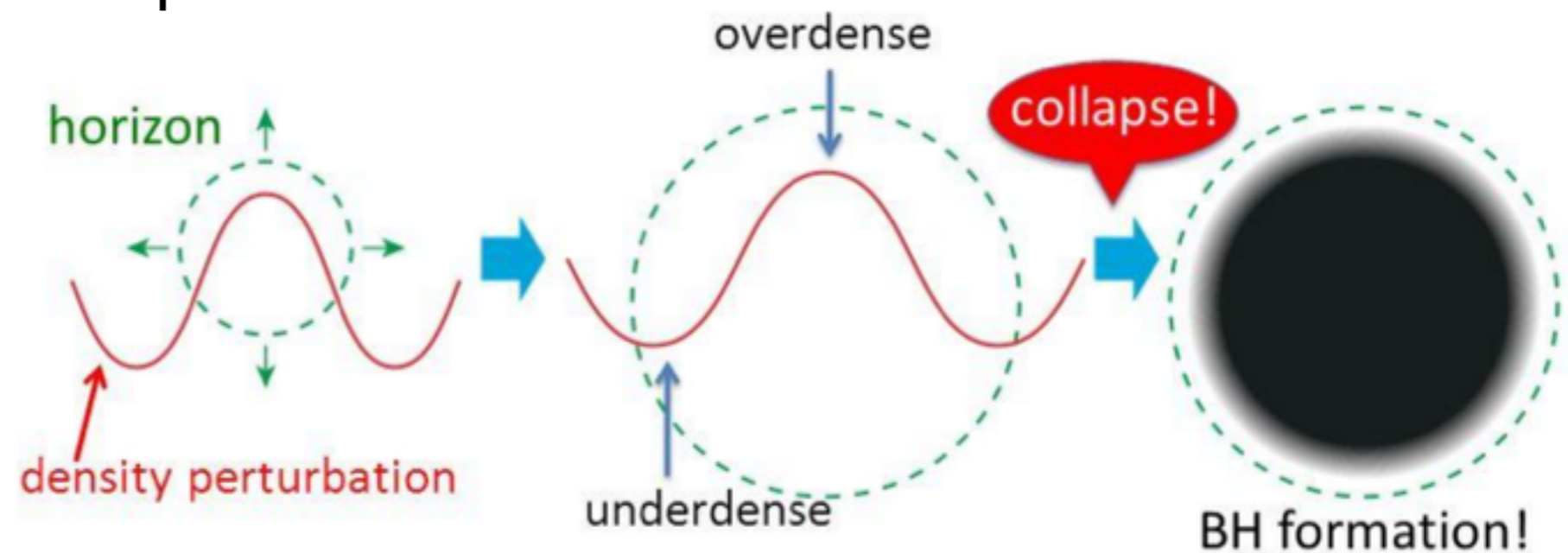


image credit: <https://slideplayer.com/slide/7773485/>

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

mass: of the order of the horizon mass

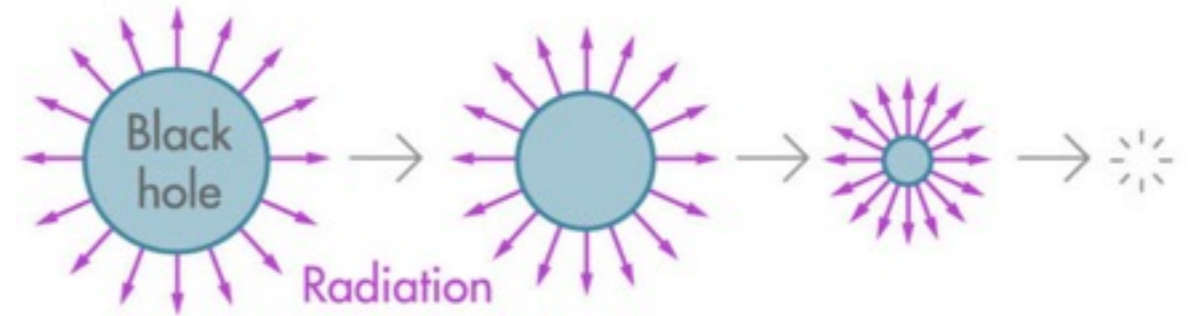
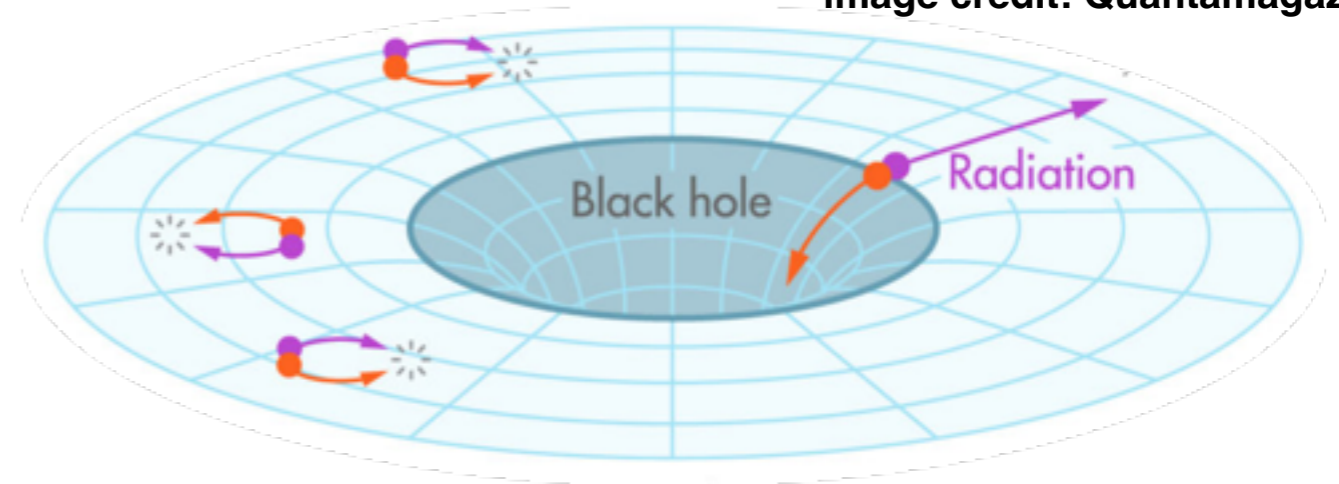
formed in a radiation dominated era:

spin: negligible

# Hawking Evaporation:

S. Hawking, 1975

image credit: Quantamagazine



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

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

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

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

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

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

$$H_I \lesssim 10^{-5} M_{\text{Pl}} \quad (\text{Planck})$$

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

evaporate before **BBN**

**Not constrained by cosmology**

# PBH Energy Content:

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

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

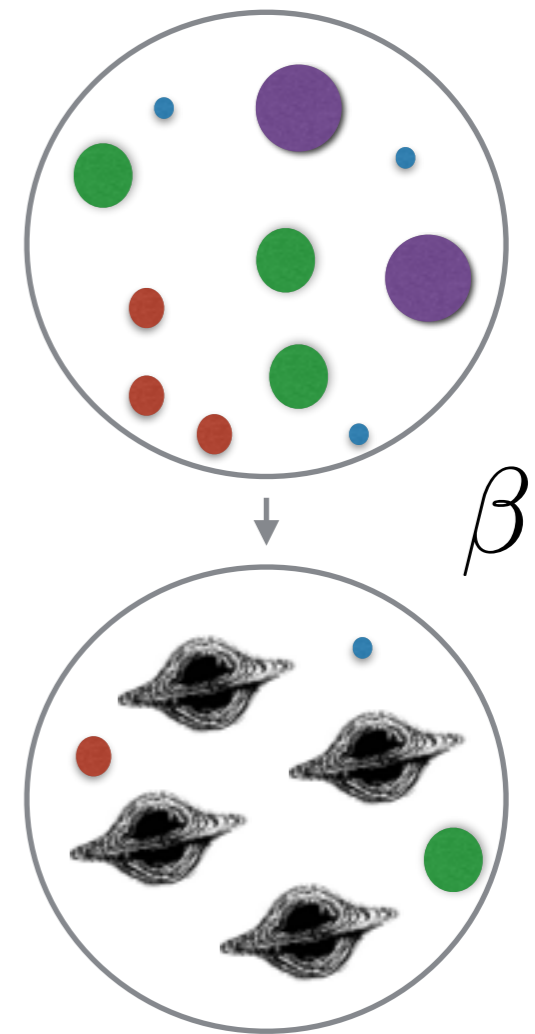
$$\rho_{\text{PBH}}(t_{\text{early-eq}}) / \rho_{\text{rad}}(t_{\text{early-eq}}) \sim 1 \quad t_{\text{early-eq}} \lesssim t_{\text{eva}}$$

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

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

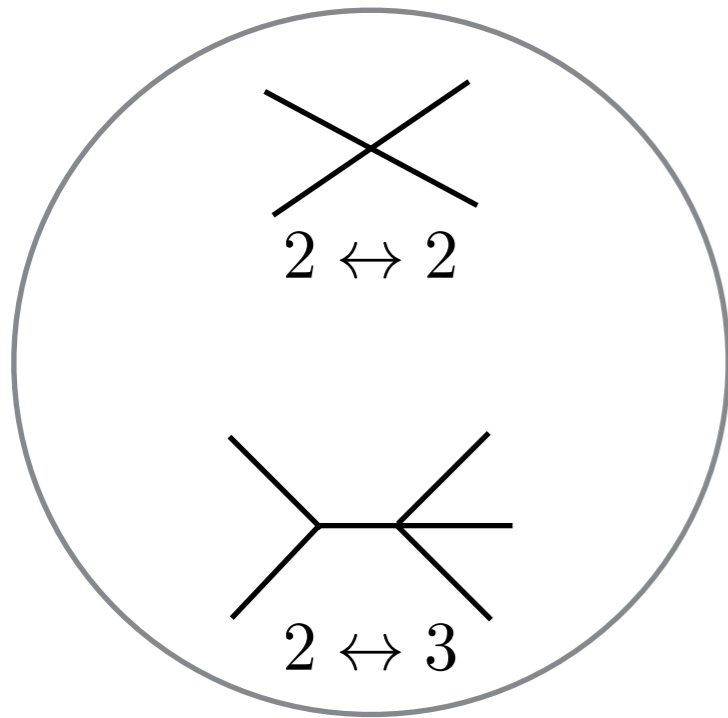
$\beta < \beta_{\text{crit}}$  evaporation happens in a RD Universe

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



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

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



Dark Sector

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


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

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


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

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

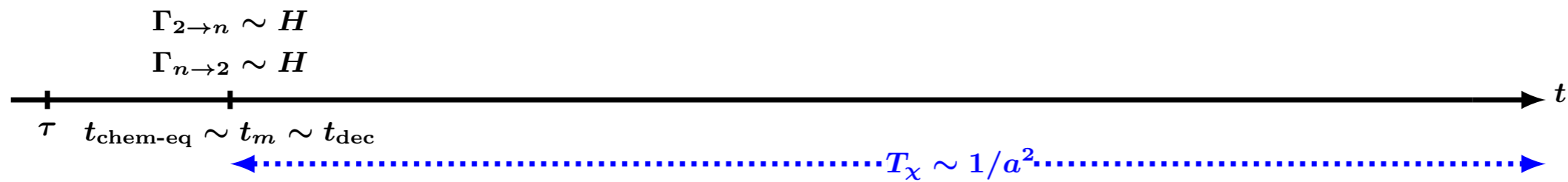

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$3 \rightarrow 2$  Cannibalism/decoupling (freeze-out):

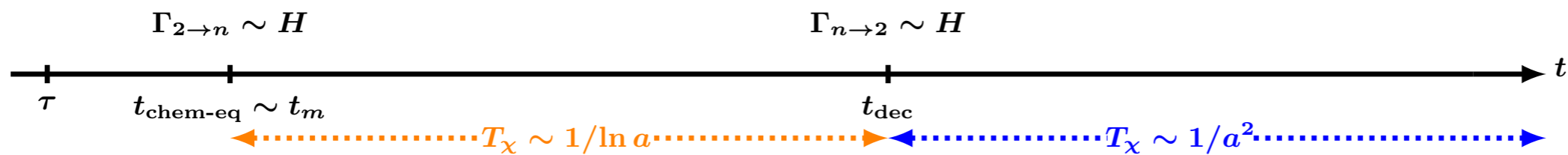
$$\frac{\Gamma_{\chi, 3 \rightarrow 2}(t)}{H(t)} \sim \frac{n_\chi^2(t) / m_\chi^5}{H(t)}, \quad t_m \lesssim t \lesssim t_{\text{dec}}$$



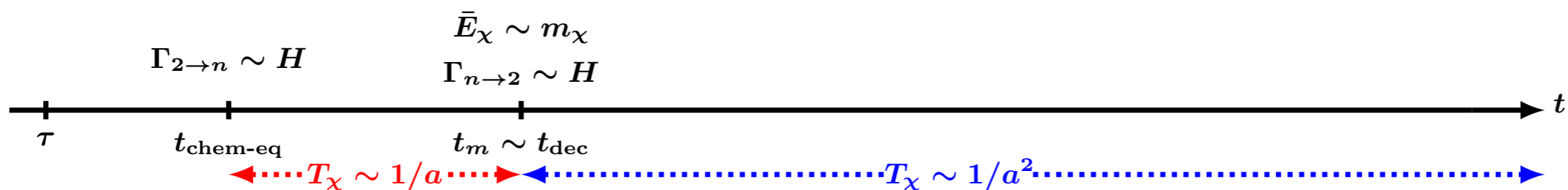
non-relativistic, no cannibalism (NRNC):



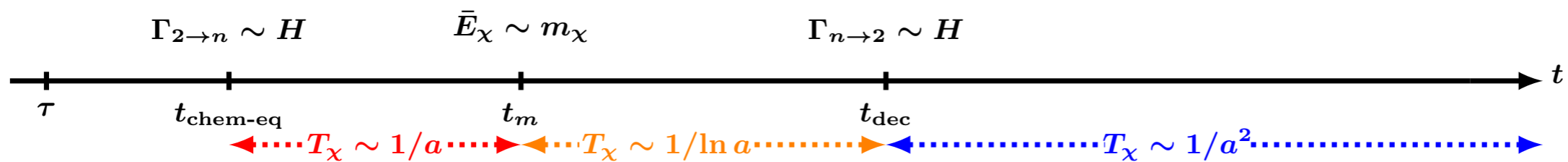
non-relativistic, with cannibalism (NRC):



relativistic, no cannibalism (RNC):



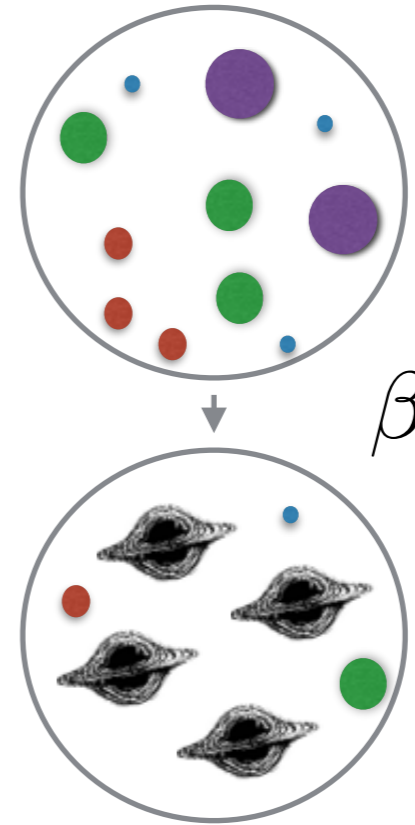
relativistic, with cannibalism (RC):



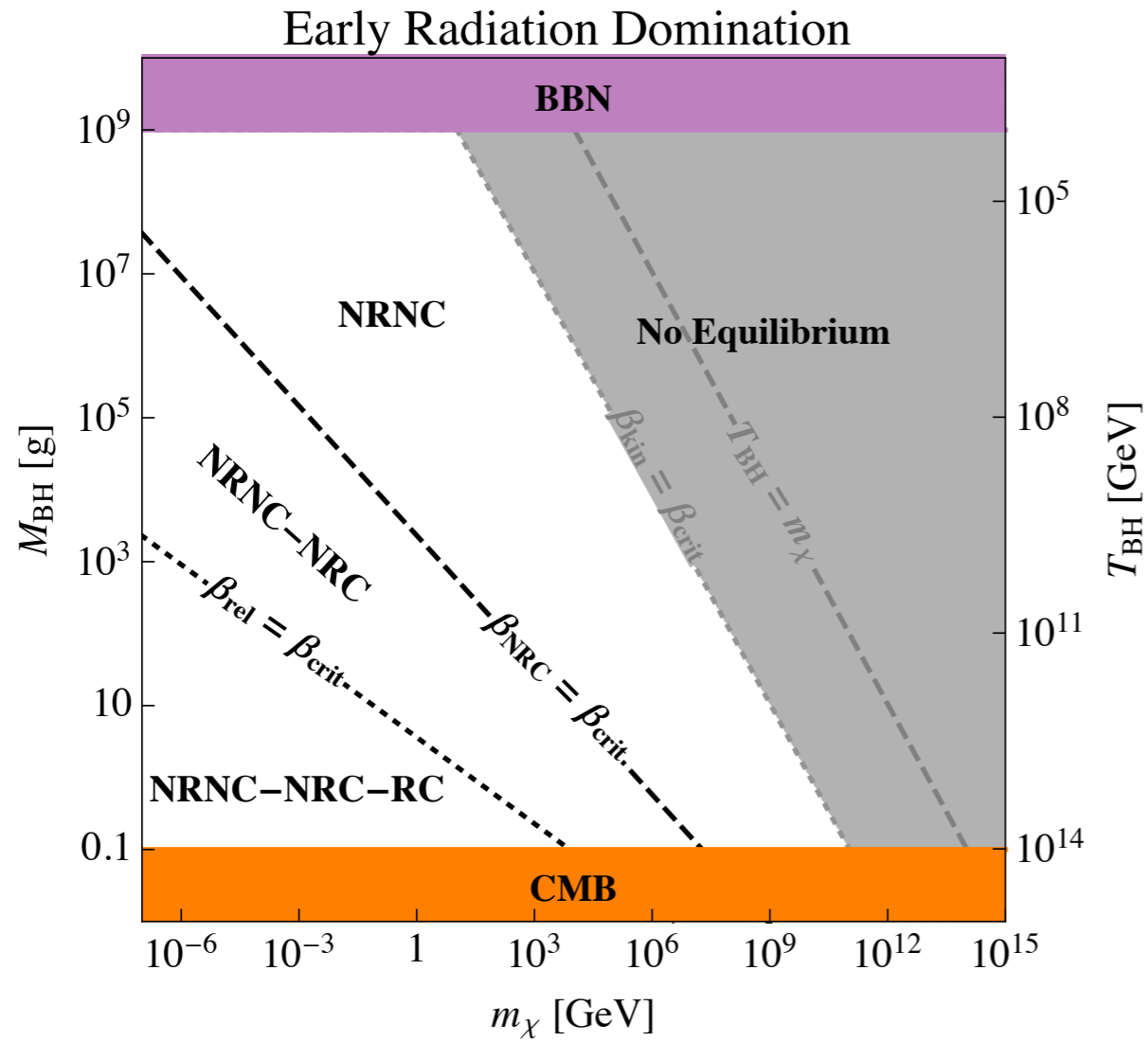
# Populating a self-interacting dark sector by Hawking evaporation of PBHs:

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

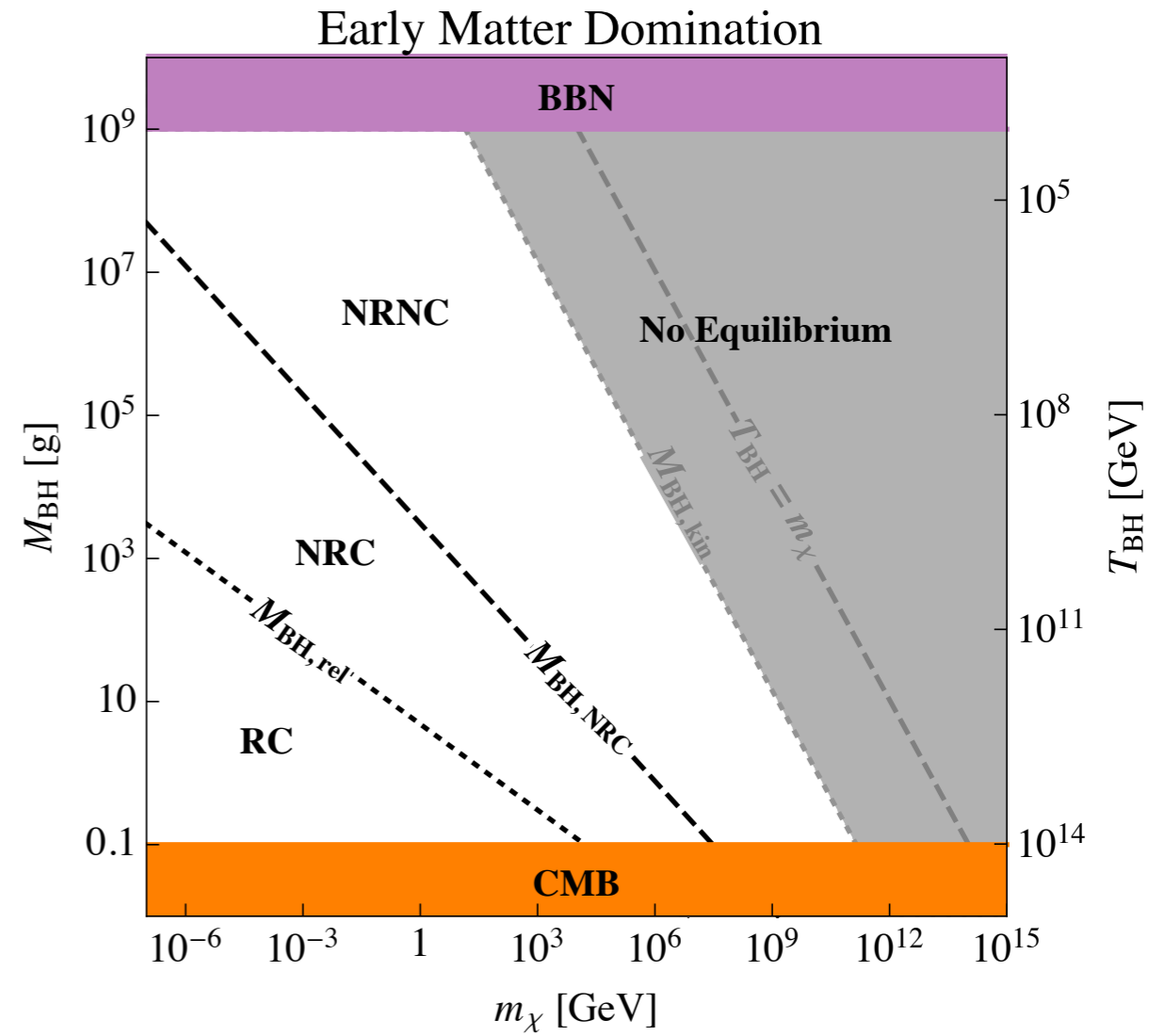
$$\beta_{\text{crit}} \sim \frac{M_{\text{Pl}}}{M_{\text{BH}}}$$



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



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

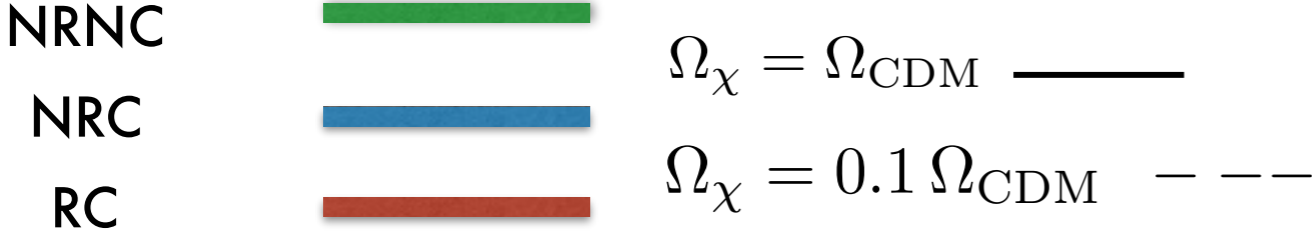


$$\beta \geq \beta_{\text{crit}}$$

$T_{\text{BH}} < m_\chi$     no equilibrium  
 relativistic: cannibalism is inevitable

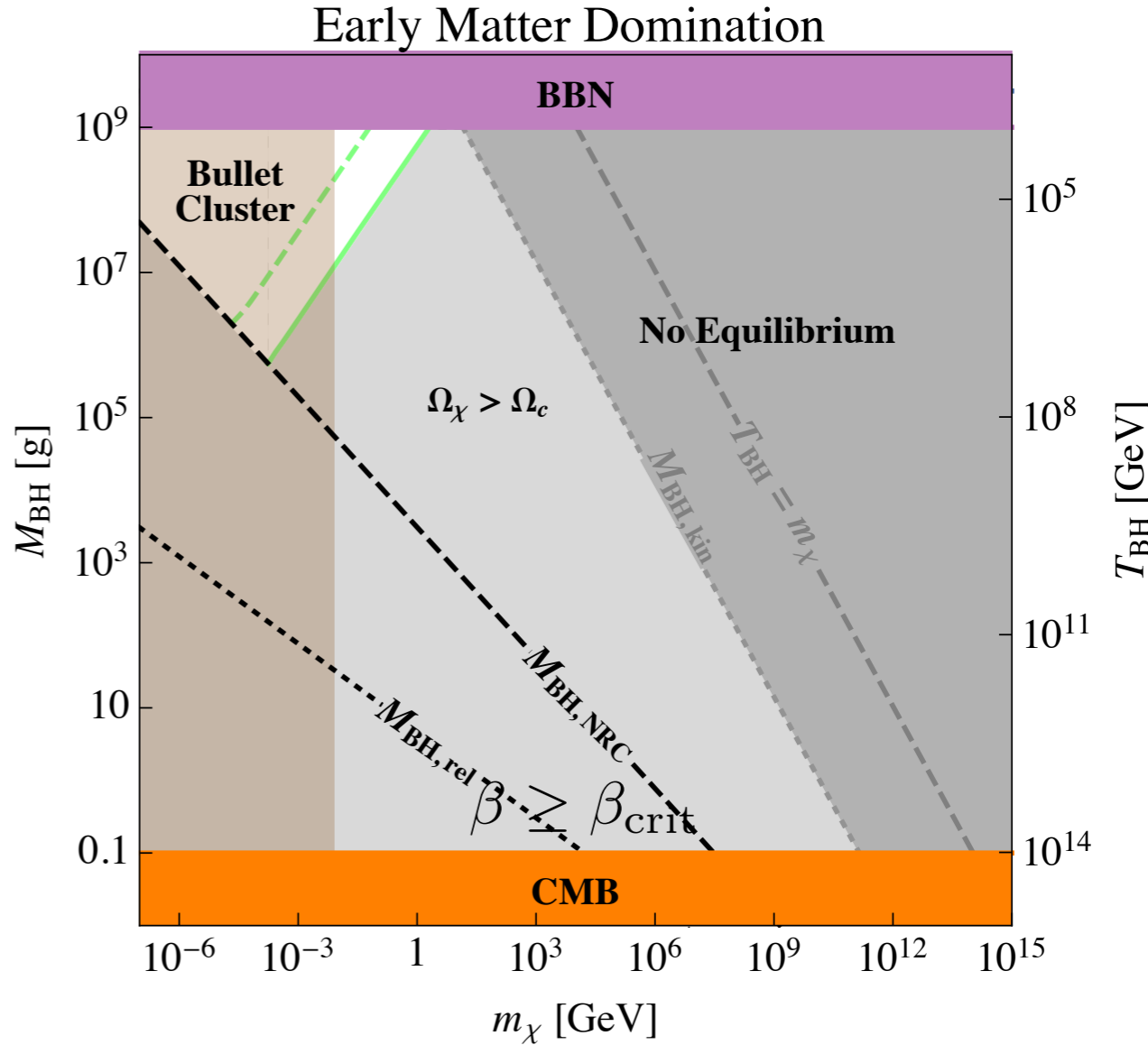
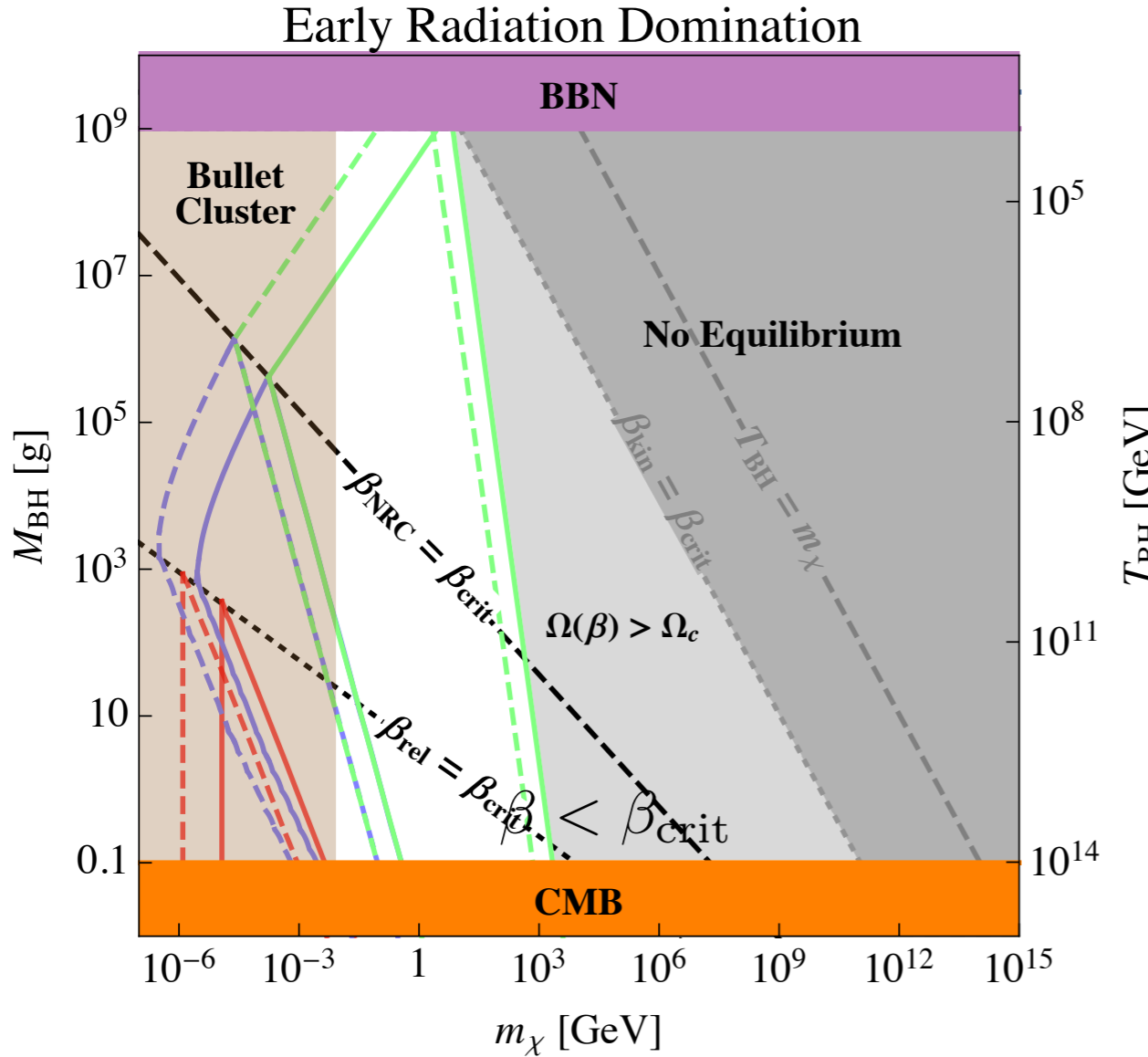
**Constraints:**

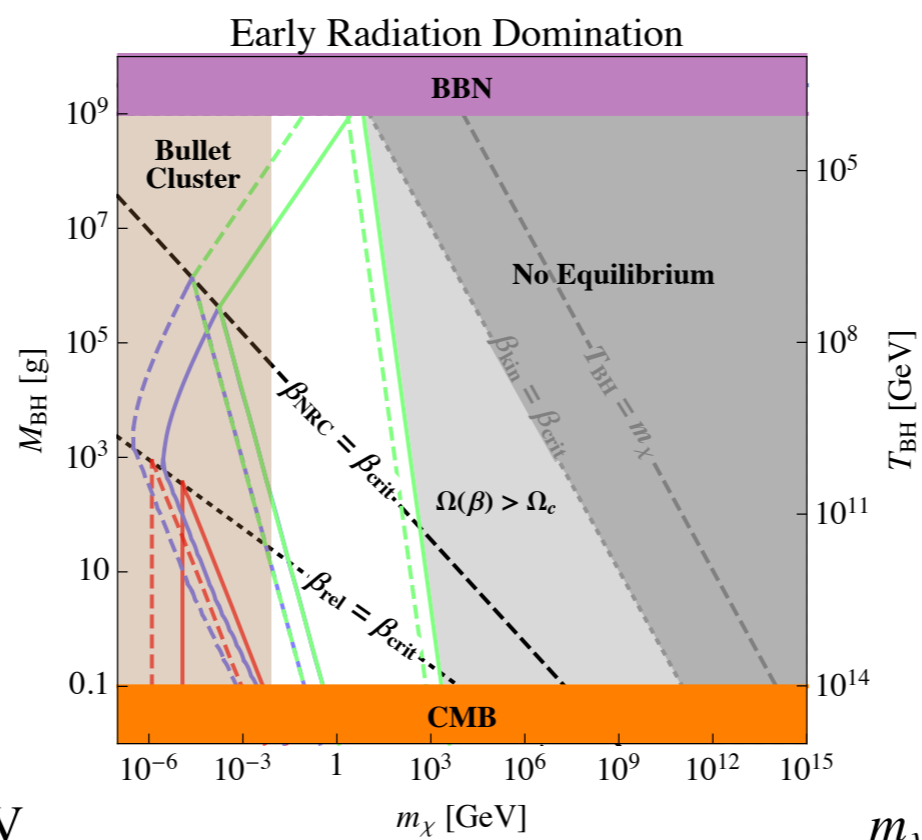
**relic abundance**



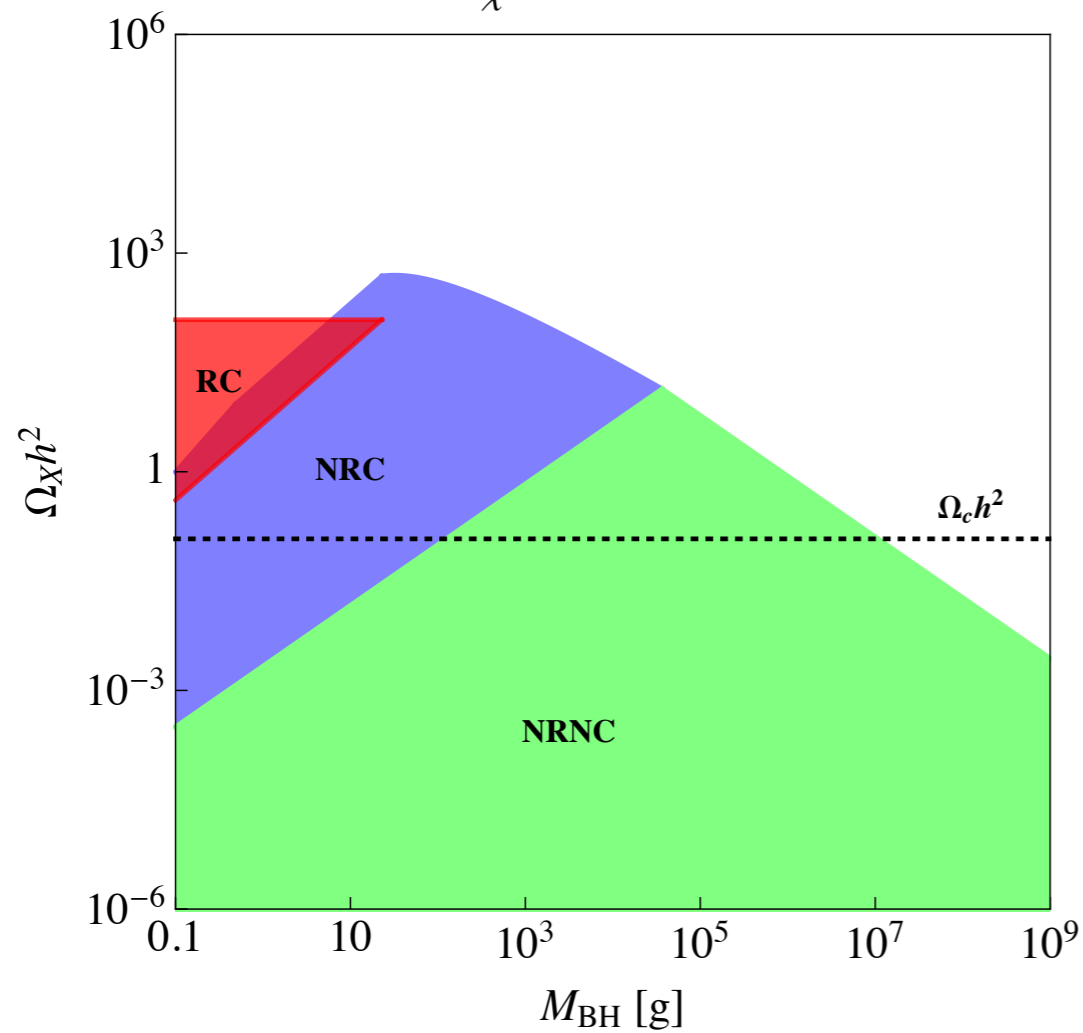
**bullet cluster**

$\sigma_{\chi\chi}/m_\chi \lesssim 1 \text{ cm}^2/\text{g}$

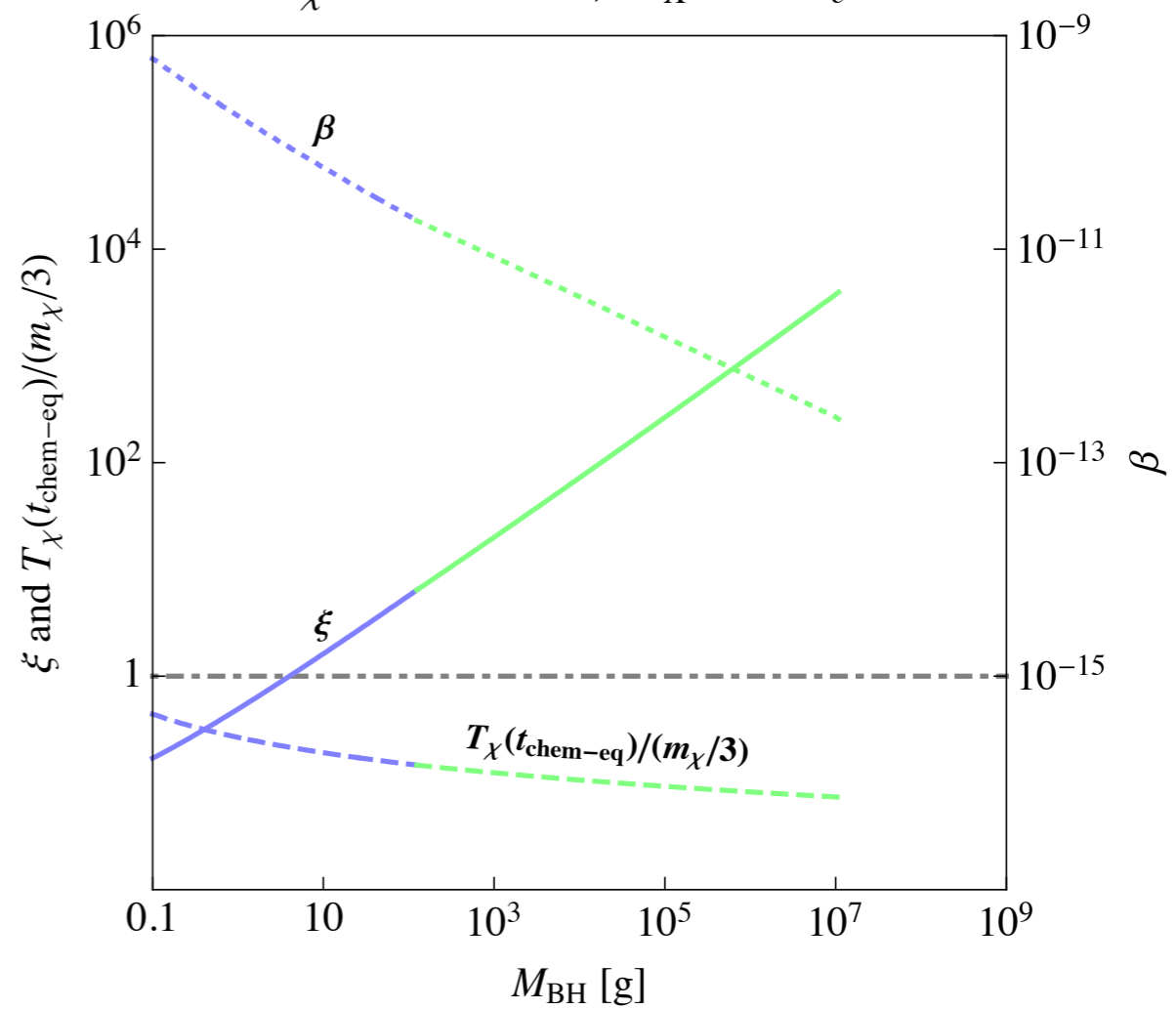




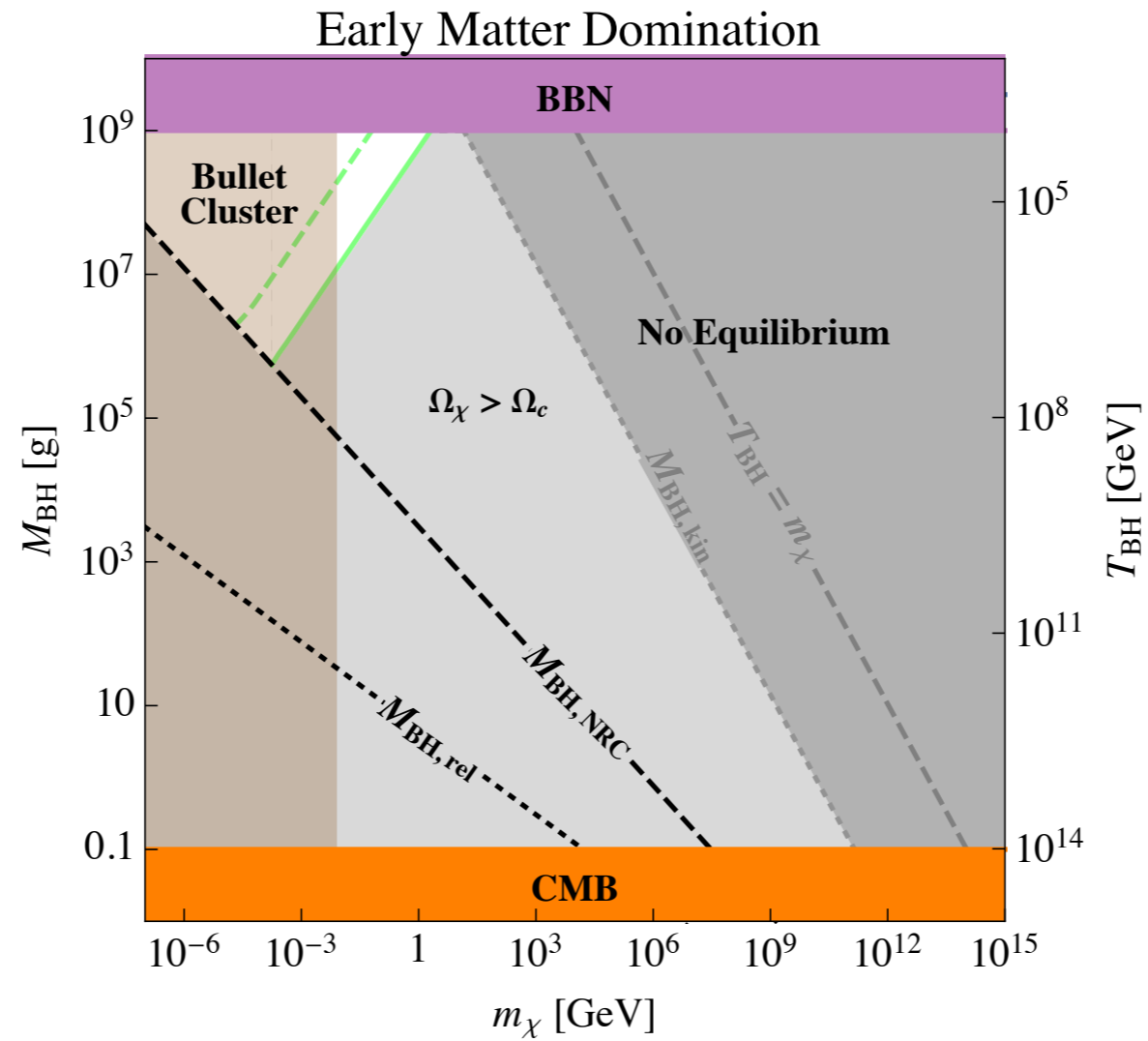
$m_\chi = 10^{-2} \text{ GeV}$



$m_\chi = 10^{-2} \text{ GeV}, \Omega_\chi h^2 = \Omega_c h^2$



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



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

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

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

## **Early radiation-dominated Universe:**

the NRNC and NRC thermal histories can accommodate  $\xi$  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  $\xi = 1$ .

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

# 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.