Effects of Primordial Black Holes on Dark Matter Models

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Outline:

- Primordial Black Holes (PBHs): formation and evolution

- PBH evaporation as a Dark Matter (DM) production mechanism

- Interplay between PBH evaporation and other well-motivated DM sources

PBHs: motivated by many different scenarios

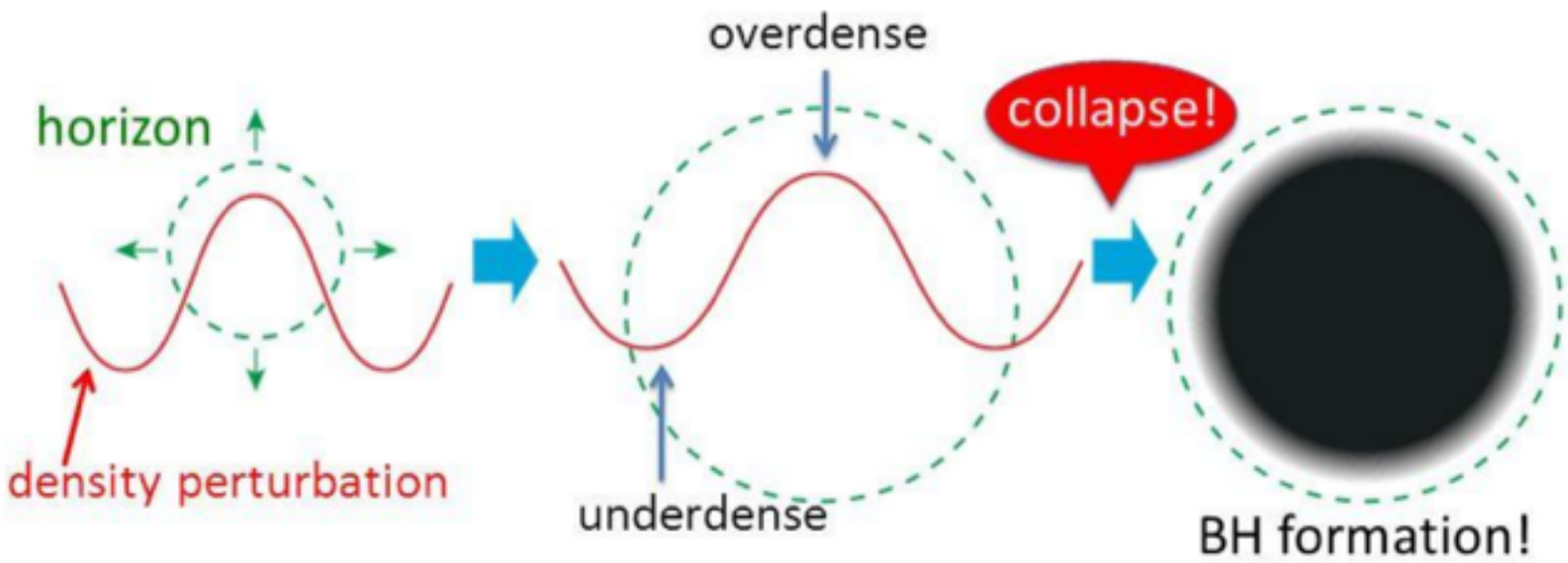


image credit: https://slideplayer.com/slide/7773485/

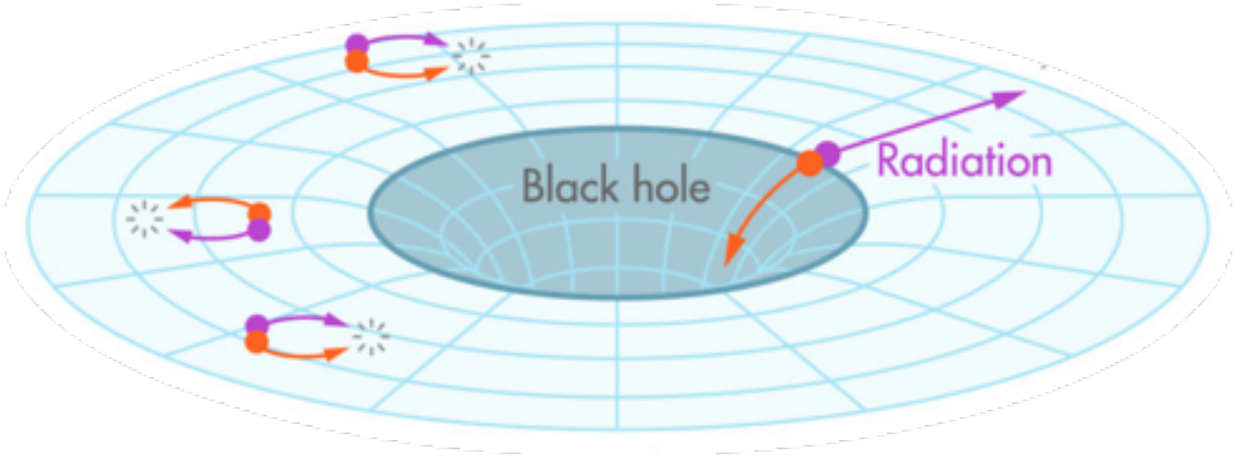
BHs can be fully characterized by their mass, spin, and charge

mass: of the order of the horizon mass

formed in a RD era:
spin: negligible

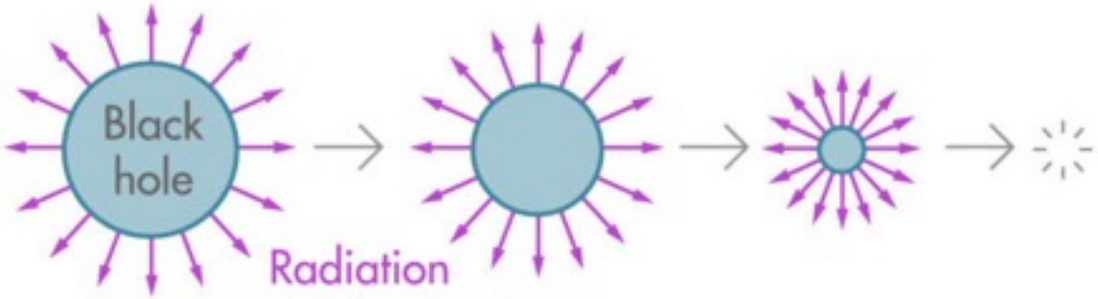
Hawking Evaporation:

image credit: Quantamagazine



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

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



$$\frac{dM_{\rm BH}}{dt} = -4\pi r_{\rm S}^2 \sum_i \int_0^\infty \frac{d^2 u_i(E,t)}{dt dE} dE$$

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

$M_{\rm BH} < 10^{15}\,{\rm g}$: would have evaporated by the present epoch

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

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

PBHs emit all the particles in the spectrum, including DM, which are lighter than their temperature.

PBH Energy Content:

initial abundance of PBHs

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

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

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

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

critical initial abundance

$$\beta_c \sim \frac{M_{\rm Pl}}{M_{\rm BH}}$$

$\beta < \beta_c$ evaporation happens in a RD Universe

$\beta \geq \beta_c$ evaporation happens in a MD Universe

DM Production via PBH evaporation in a RD Universe: $\beta < \beta_c$

$$\Omega_\chi h^2 \simeq 7.3 \times 10^7 \beta \left(\frac{g_*(T_i)}{106.8}\right)^{-1/4} \left(\frac{\gamma}{0.2}\right)^{1/2} \left(\frac{m_\chi}{\mathrm{GeV}}\right) \left(\frac{g_\chi}{g_*(T_{\mathrm{BH}})}\right) \left(\frac{M_{\mathrm{BH}}}{M_{\mathrm{Pl}}}\right)^{1/2}, \qquad T_{\mathrm{BH}} > m_\chi$$

$$\Omega_\chi h^2 \simeq 1.2 \times 10^5 \beta \left(\frac{g_*(T_i)}{106.8}\right)^{-1/4} \left(\frac{\gamma}{0.2}\right)^{1/2} \left(\frac{m_\chi}{\mathrm{GeV}}\right) \left(\frac{g_\chi}{g_*(T_{\mathrm{BH}})}\right) \left(\frac{M_{\mathrm{Pl}}^7}{M_{\mathrm{BH}}^3 m_\chi^4}\right)^{1/2}, \qquad T_{\mathrm{BH}} < m_\chi$$

DM Production via PBH evaporation in MD Universe: $\beta \geq \beta_c$

$$\Omega_\chi h^2 \simeq 1.1 \times 10^7 \left(\frac{g_*(T_{\text{eva-BH}})}{106.8}\right)^{1/4} \left(\frac{g_\chi}{g_*(T_{\mathrm{BH}})}\right) \left(\frac{m_\chi}{\mathrm{GeV}}\right) \left(\frac{M_{\mathrm{Pl}}}{M_{\mathrm{BH}}}\right)^{1/2}, \qquad T_{\mathrm{BH}} > m_\chi$$

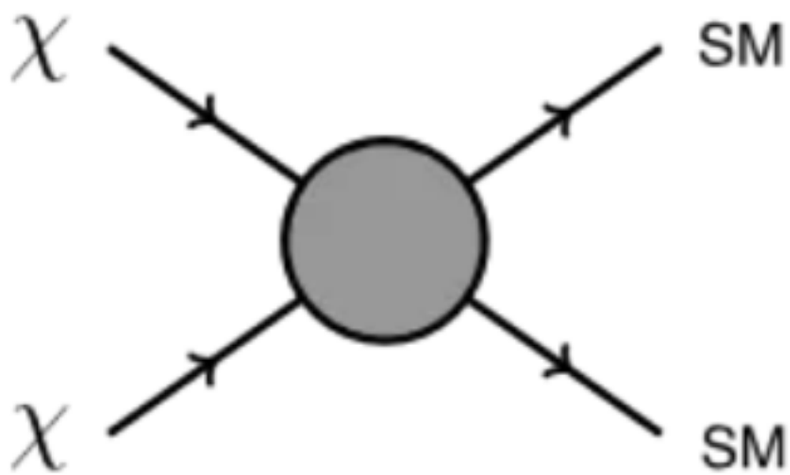
$$\Omega_\chi h^2 \simeq 1.7 \times 10^4 \left(\frac{g_*(T_{\text{eva-BH}})}{106.8}\right)^{1/4} \left(\frac{g_\chi}{g_*(T_{\mathrm{BH}})}\right) \left(\frac{m_\chi}{\mathrm{GeV}}\right) \left(\frac{M_{\mathrm{Pl}}^9}{M_{\mathrm{BH}}^5 m_\chi^4}\right)^{1/2}, \qquad T_{\mathrm{BH}} < m_\chi$$

Alternative DM production mechanisms:

- Freeze-out (WIMP, SIMP)
- Freeze-in
- Gravitational production of superheavy DM

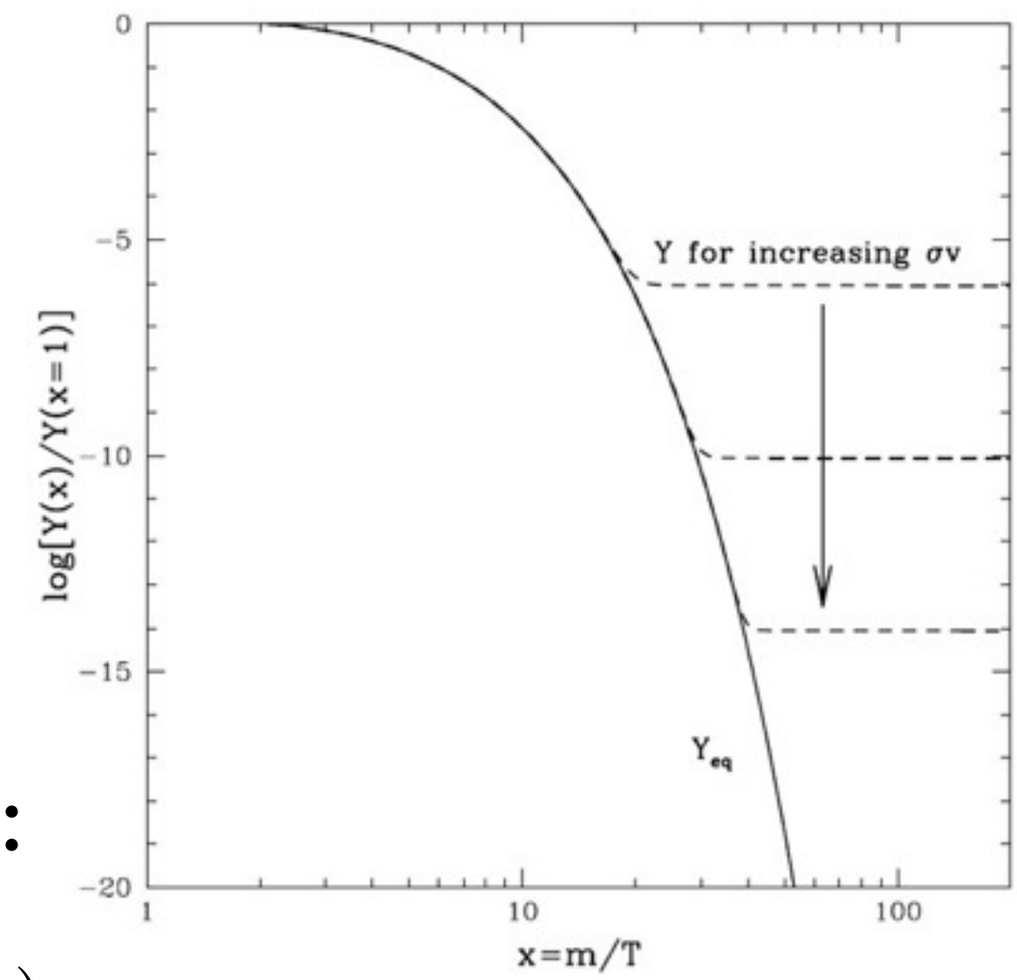
Interplay between PBH evaporation and other production mechanism?

Freeze-out: WIMP case



$$\dot{n}_\chi + 3Hn_\chi = -\langle\sigma v\rangle\left(n_\chi^2 - n_{\chi,\mathrm{eq}}^2\right)$$

$$\Omega_\chi^{\text{fr-out}}(\langle\sigma v\rangle)h^2 \simeq \frac{3.79\,x_f}{g_*^{1/2}}\frac{s_0}{M_{\mathrm{Pl}}\rho_c\langle\sigma v\rangle}h^2$$



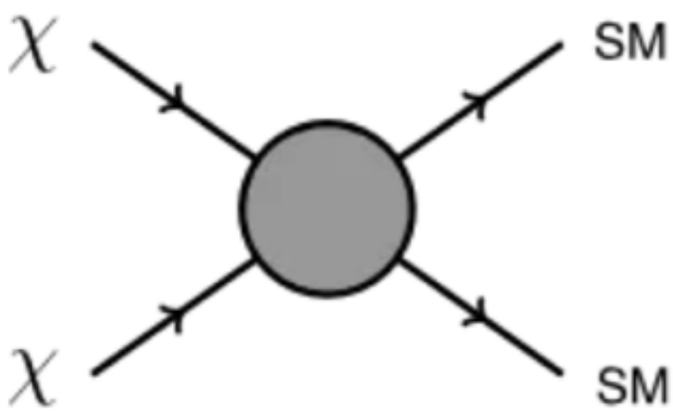
weak-scale couplings,
weak scale mass

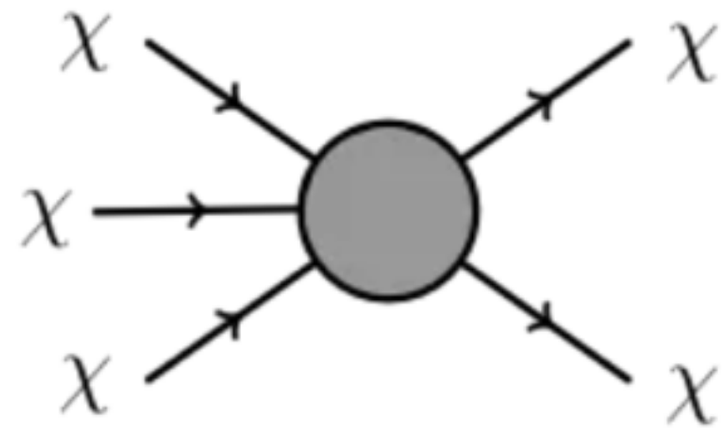
PBH evaporation +WIMP freeze-out:

$$\Omega_\chi^{\text{fr-out}}(\langle\sigma v\rangle)h^2 \leq \Omega_{\mathrm{c}}h^2, \qquad (t_{\mathrm{eva}} < t_{\text{fr-out}})$$

$$\Omega_\chi^{\text{fr-out}}(\langle\sigma v\rangle)h^2 + \Omega_\chi^{\mathrm{BH}}(m_\chi, M_{\mathrm{BH}}, \beta)h^2 \leq \Omega_{\mathrm{c}}h^2, \qquad (t_{\mathrm{eva}} > t_{\text{fr-out}})$$

Freeze-out: SIMP case





strong couplings, strong-scale mass

$$\dot{n}_\chi + 3Hn_\chi = -\langle \sigma v^2 \rangle \left(n_\chi^3 - n_\chi^2 n_{\chi,\mathrm{eq}} \right)$$

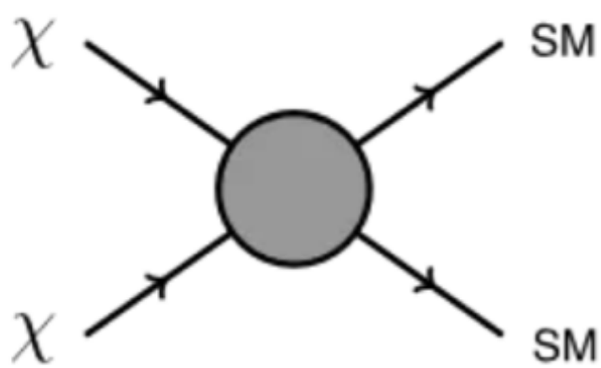
$$\Omega_\chi^{\text{fr-out}}(m_\chi, \langle \sigma v^2 \rangle) h^2 \simeq \frac{3\sqrt{3}\, 5^{3/4} x_f^2}{\pi^{5/4} g_*^{3/4}} \frac{s_0}{\sqrt{M_{\mathrm{Pl}}} m_\chi \rho_c \sqrt{\langle \sigma v^2 \rangle}} h^2$$

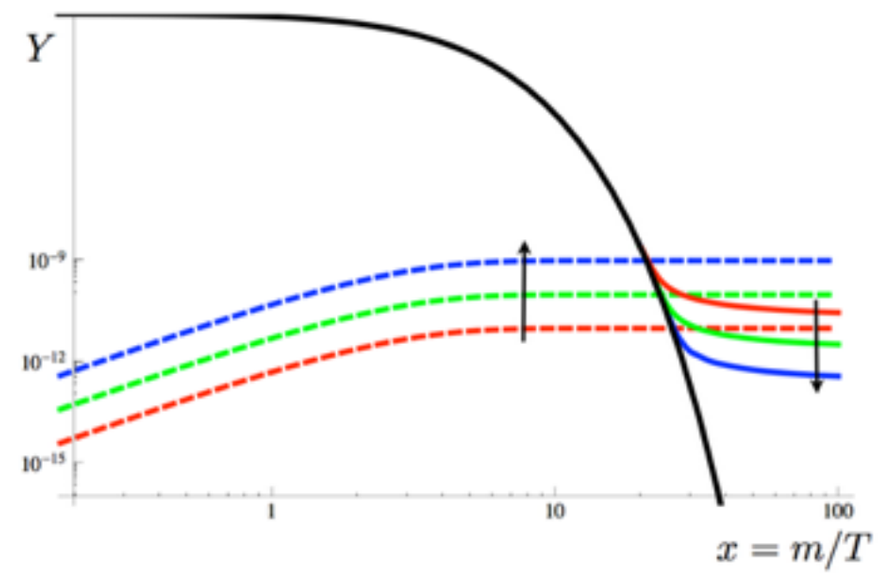
PBH evaporation +SIMP freeze-out:

$$\Omega_\chi^{\text{fr-out}}(m_\chi, \langle \sigma v^2 \rangle) h^2 \leq \Omega_{\mathrm{c}} h^2, \qquad (t_{\mathrm{eva}} < t_{\text{fr-out}})$$

$$\Omega_\chi^{\text{fr-out}}(m_\chi, \langle \sigma v^2 \rangle) h^2 + \Omega_\chi^{\mathrm{BH}}(m_\chi, M_{\mathrm{BH}}, \beta) h^2 \leq \Omega_{\mathrm{c}} h^2, \qquad (t_{\mathrm{eva}} > t_{\text{fr-out}})$$

Freeze-in:





$$\dot{n}_\chi + 3Hn_\chi \approx \int d\Pi_{B_1} d\Pi_{B_2} d\Pi_{\chi_1} d\Pi_{\chi_2} (2\pi)^4 \delta^4(p_{B_1} + p_{B_2} - p_{\chi_1} - p_{\chi_2}) |M_{B_1 B_2 \to \chi_1 \chi_2}|^2 f_{B_1} f_{B_2}$$

produce DM particles with masses up to $T_{\rm reh}$

$$\Omega_\chi(\lambda) h^2 \simeq \frac{405\sqrt{5}\lambda^2}{16384\,\pi^{13/2} g_*^{3/2}} \frac{M_{\rm Pl} s_0}{\rho_c} h^2$$

PBH evaporation + freeze-in:

$$\Omega_\chi^{\text{fr-in}}(\lambda) h^2 + \Omega_\chi^{\rm BH}(m_\chi, M_{\rm BH}, \beta) h^2 \leq \Omega_{\rm c} h^2$$

Gravitational Production of Superheavy DM (WIMPZILLA):

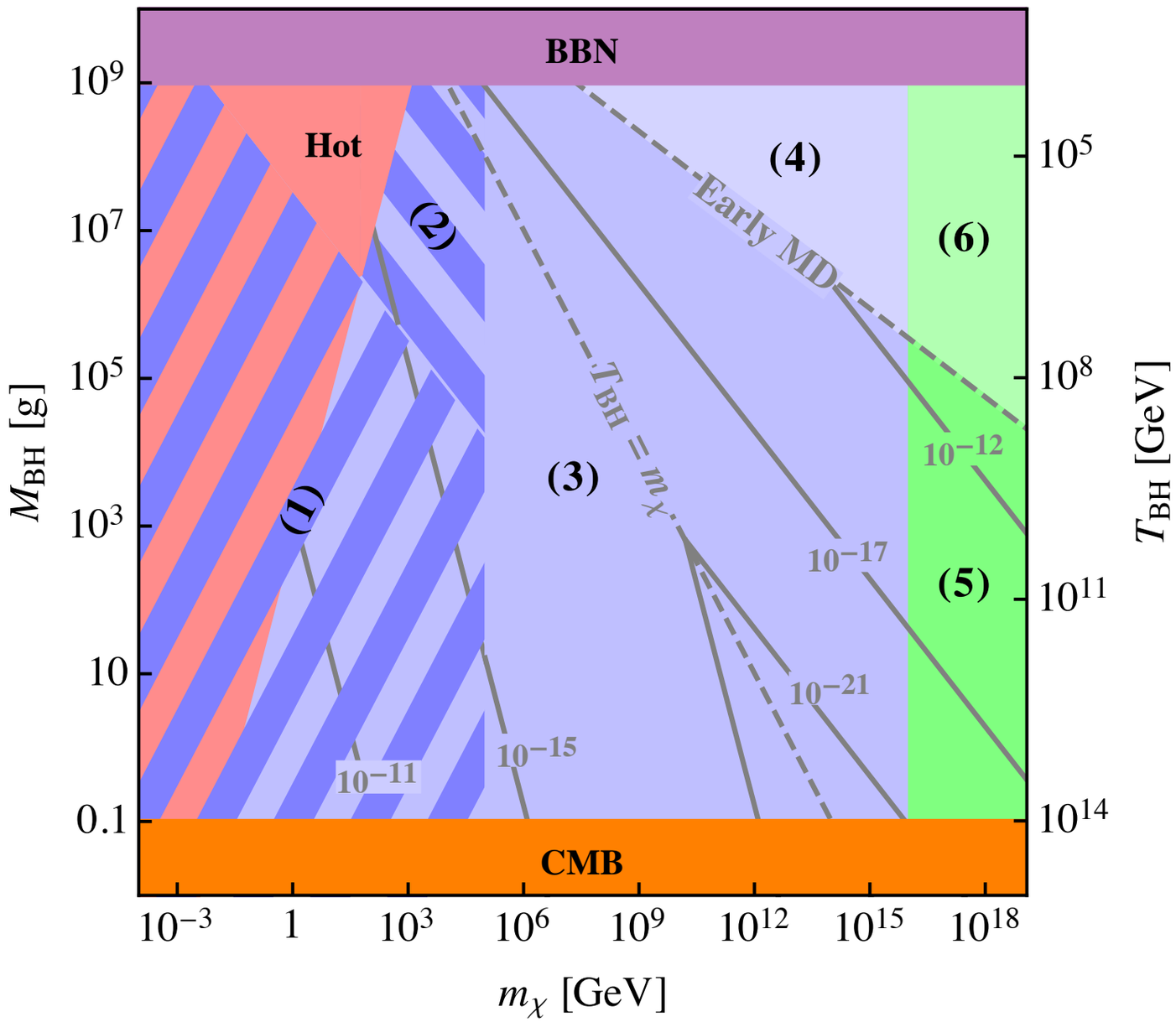
gravitational particle creation by the expansion of the universe acting on quantum fluctuations of the vacuum.

e.g., produced at the end of inflation, during the reheating process, preheating process, in bubble collisions in a first-order, phase transition that completes inflation, ...

can produce DM particles with masses up to Planck mass

PBH evaporation + WIMPZILLA:

$$\Omega_\chi^{\rm WIMPZILLA}(m_\chi, g)h^2 + \Omega_\chi^{\rm BH}(m_\chi, M_{\rm BH}, \beta)h^2 \leq \Omega_{\rm c}h^2$$



Sources of Dark Matter:

(1): freeze−out only

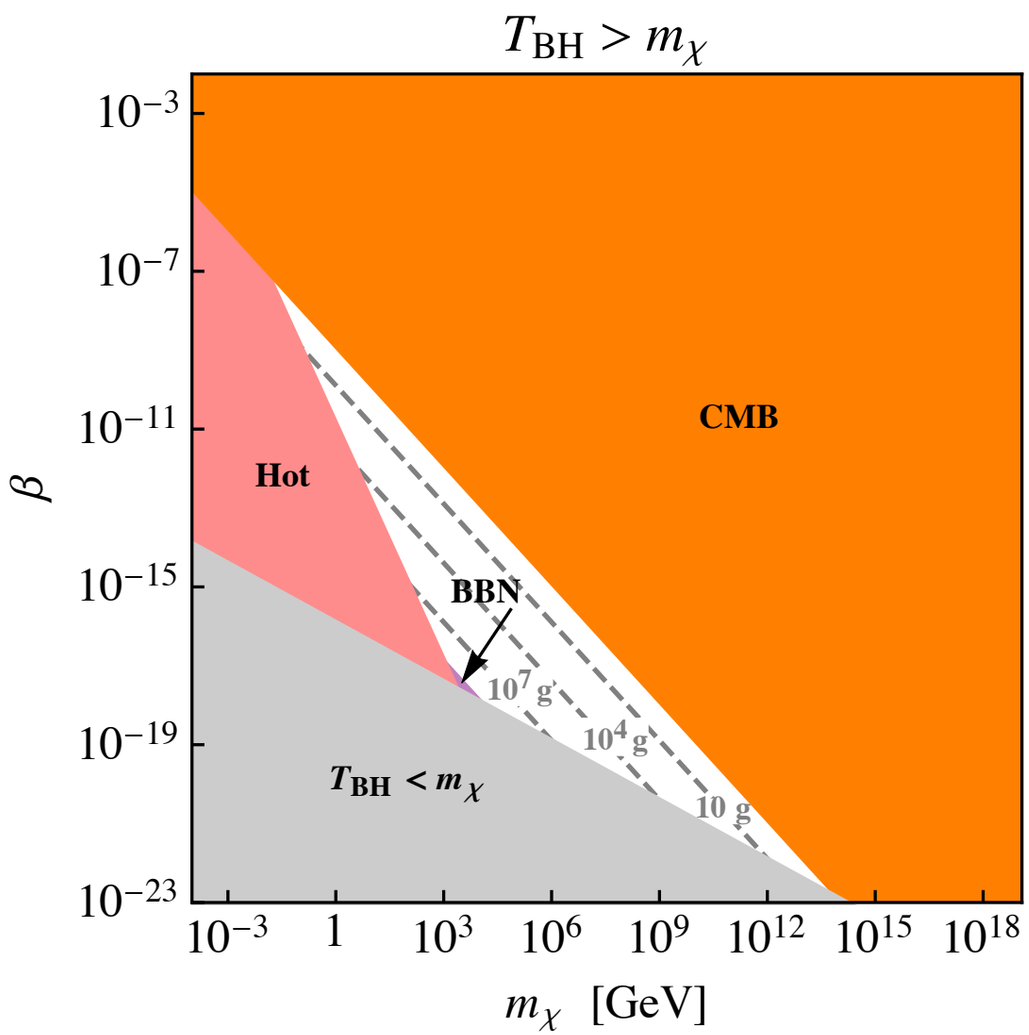
(2): freeze−out and/or PBH

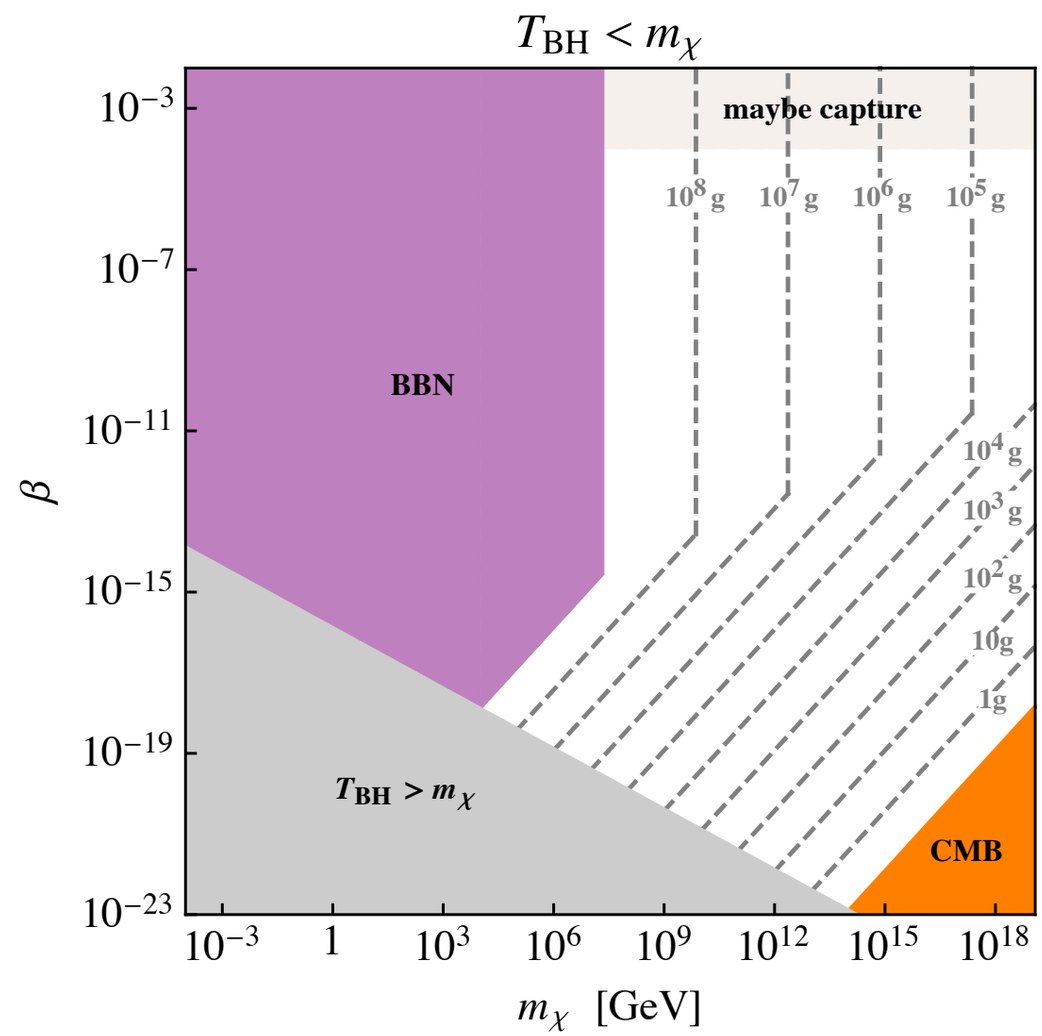
(3): freeze−in and/or PBH

(4): freeze−in required plus PBH

(5): WIMPZILLA and/or PBH

(6): WIMPZILLA required plus PBH


$T_{\rm BH} > m_\chi$
CMB
Hot
BBN
10^7 g
10^4 g
10 g
$T_{\rm BH} < m_\chi$
β
m_χ [GeV]


$T_{\rm BH} < m_\chi$
maybe capture
10^8 g
10^7 g
10^6 g
10^5 g
BBN
10^4 g
10^3 g
10^2 g
10g
1g
$T_{\rm BH} > m_\chi$
CMB
β
m_χ [GeV]

Conclusions

- Hawking evaporation of PBHs provides a novel mechanism for producing DM.

- The interplay between PBHs and the alternative sources of DM can give rise to model-independent modifications to the required DM abundance from each production mechanism, which in turn affect the prospects for dark matter detection.