Dark matter production from evaporation of regular primordial black holes

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[2510.09395]

Types of black holes (BHs)

- Stellar-mass BHs: mass ~a few-100 solar masses
- Intermediate-mass BHs? From 100 to 100 000 solar masses
- Supermassive BHs: mass >100 000 solar masses
- Primordial black holes (PBHs): from mass of ~1 g to ~ 100 000 solar masses. This range could be extended under certain conditions

Motivations for PBHs

- LIGO/Virgo detection of gravitational waves (GWs) from binary BHs mergers: ~ a few tens solar masses

- Too early supermassive black holes (at z~10) observed by James Webb space telescope: ~ 10^6-10^7 solar masses

- The identity of dark matter (DM)

- Unusual high-energy cosmic rays

Regular primordial black holes (RPBHs) have the same motivations as singular PBHs, plus:

- No singularity
- Potential evidences for cosmologically coupled BHs

Static, spherically symmetric RPBHs

$$ds^2 = -f(r)dt^2 + \frac{dr^2}{g(r)} + h(r)d\Omega^2,$$

$$\text{Hayward:} \begin{cases} f_{\text{Hay}}(r) = g_{\text{Hay}}(r) = 1 - \frac{2GMr^2}{r^3+2GML^2} \\ h_{\text{Hay}}(r) = r^2 \end{cases}$$

$$\text{Simpson-Visser:} \begin{cases} f_{\text{SV}}(r) = g_{\text{SV}}(r) = 1 - \frac{2GM}{\sqrt{r^2+L^2}} \\ h_{\text{SV}}(r) = r^2 + L^2 \end{cases}$$

Evaporation of RPBHs

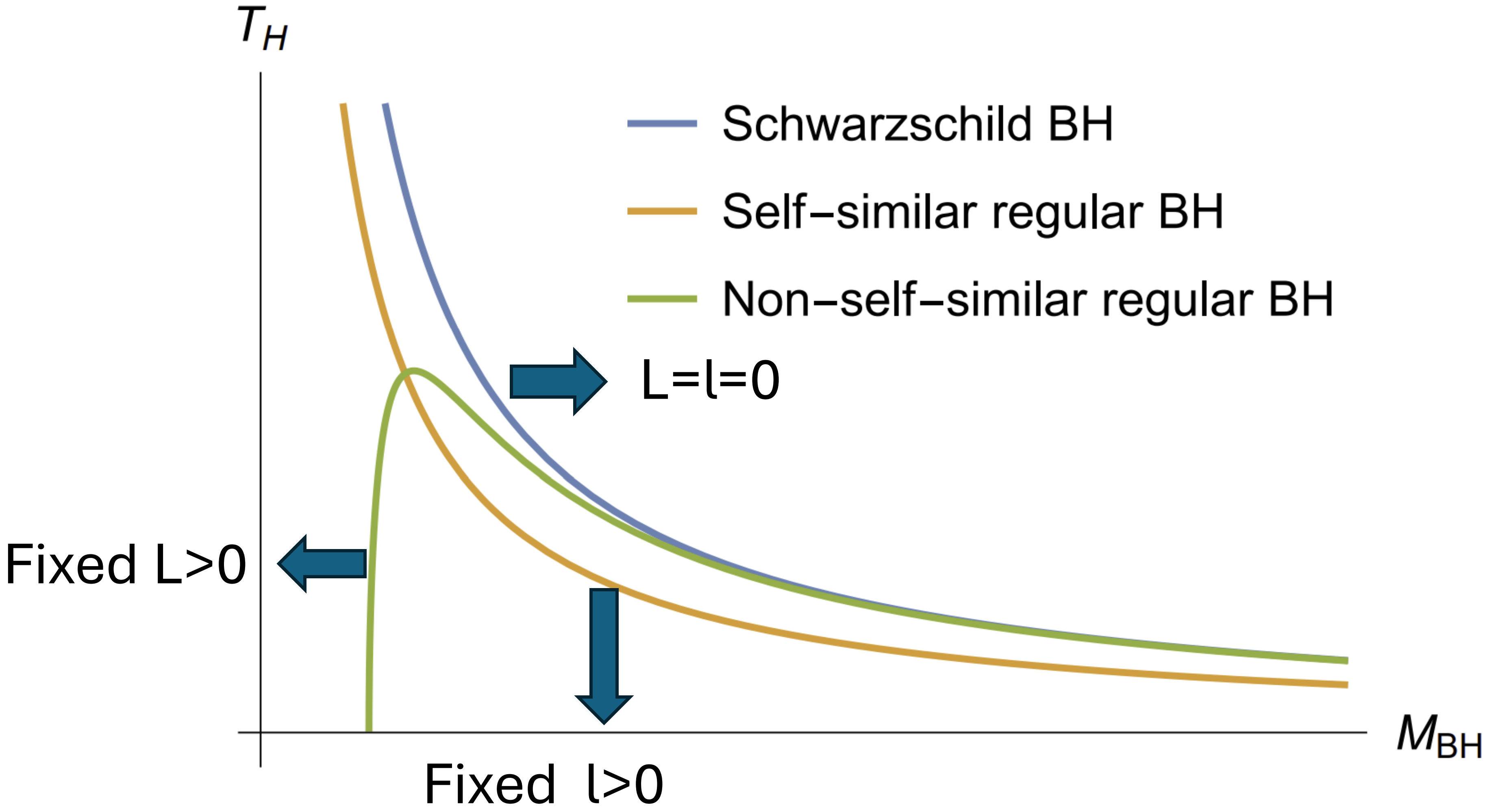
$$T_{\rm H} = \frac{\kappa}{2\pi} = \frac{f'(r)}{4\pi}\sqrt{\frac{g(r)}{f(r)}}\bigg|_{r=r_{\rm H}},$$

$$A(l) \equiv \frac{T_{\rm H}}{T_{\rm Sch}} \quad , \quad B(l) \equiv \frac{r_{\rm H}}{r_{\rm Sch}}. \quad\quad l \equiv \frac{L}{GM}.$$

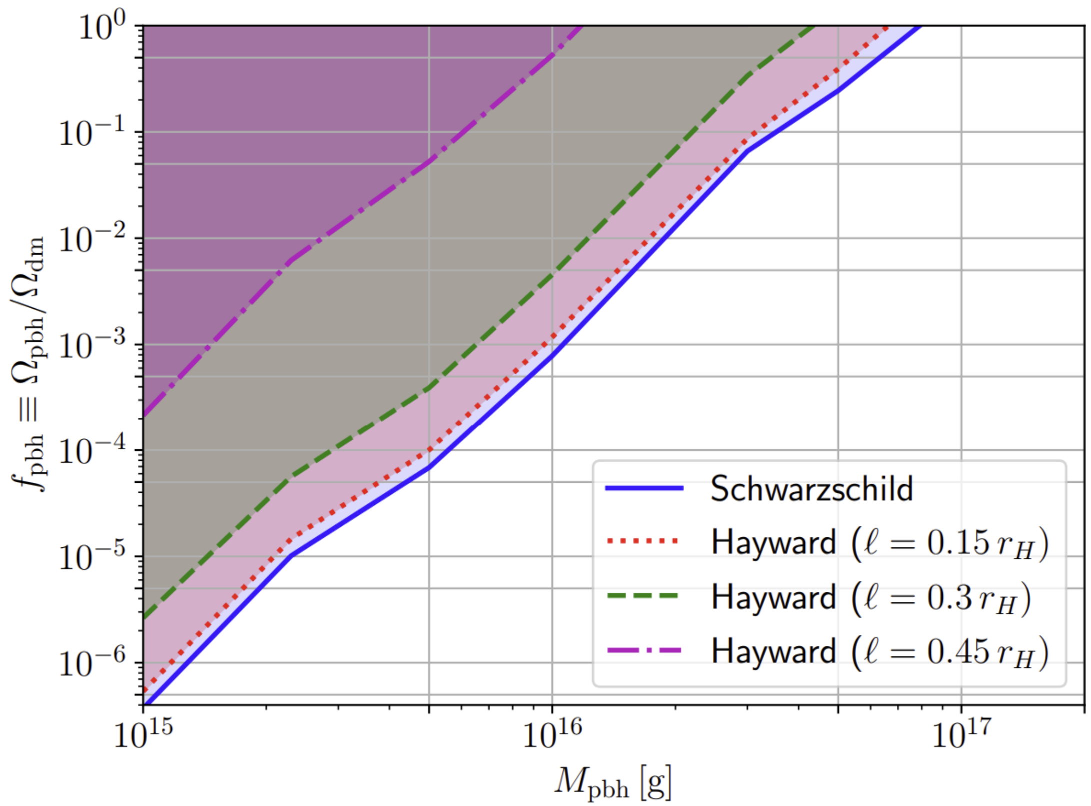
$$T_{\rm Sch} = \frac{1}{8\pi GM} \quad , \quad r_{\rm Sch} = 2GM.$$

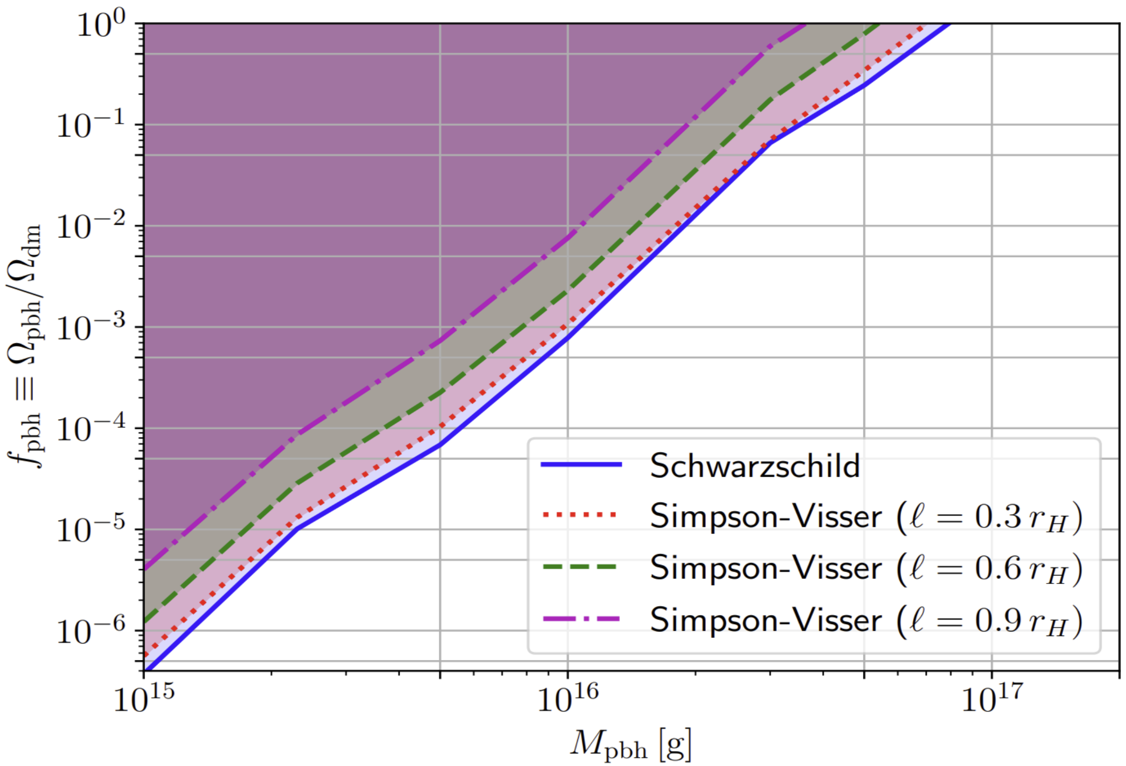
Types of BHs

$$T_{\rm H} = T_{\rm Sch}\sqrt{1-\left(\frac{L}{2GM}\right)^2} = \frac{1}{8\pi GM}\sqrt{1-\left(\frac{l}{2}\right)^2},$$



Heavy self-similar RPBHs as DM





Note: ℓ in their papers is L in our paper. They effectively fixed the ratio L/GM, which is l in our paper.

Calza, Pedrotti, Vagnozzi, [2409.02804]

Calza, Pedrotti, Vagnozzi, [2409.02807]

What we propose:

Particle DM is produced from evaporation of ultra-light self-similar RPBHs

Properties of RPBHs

$$M(t) = M_i \left(1 - \frac{t - t_i}{\tau}\right)^{1/3}$$

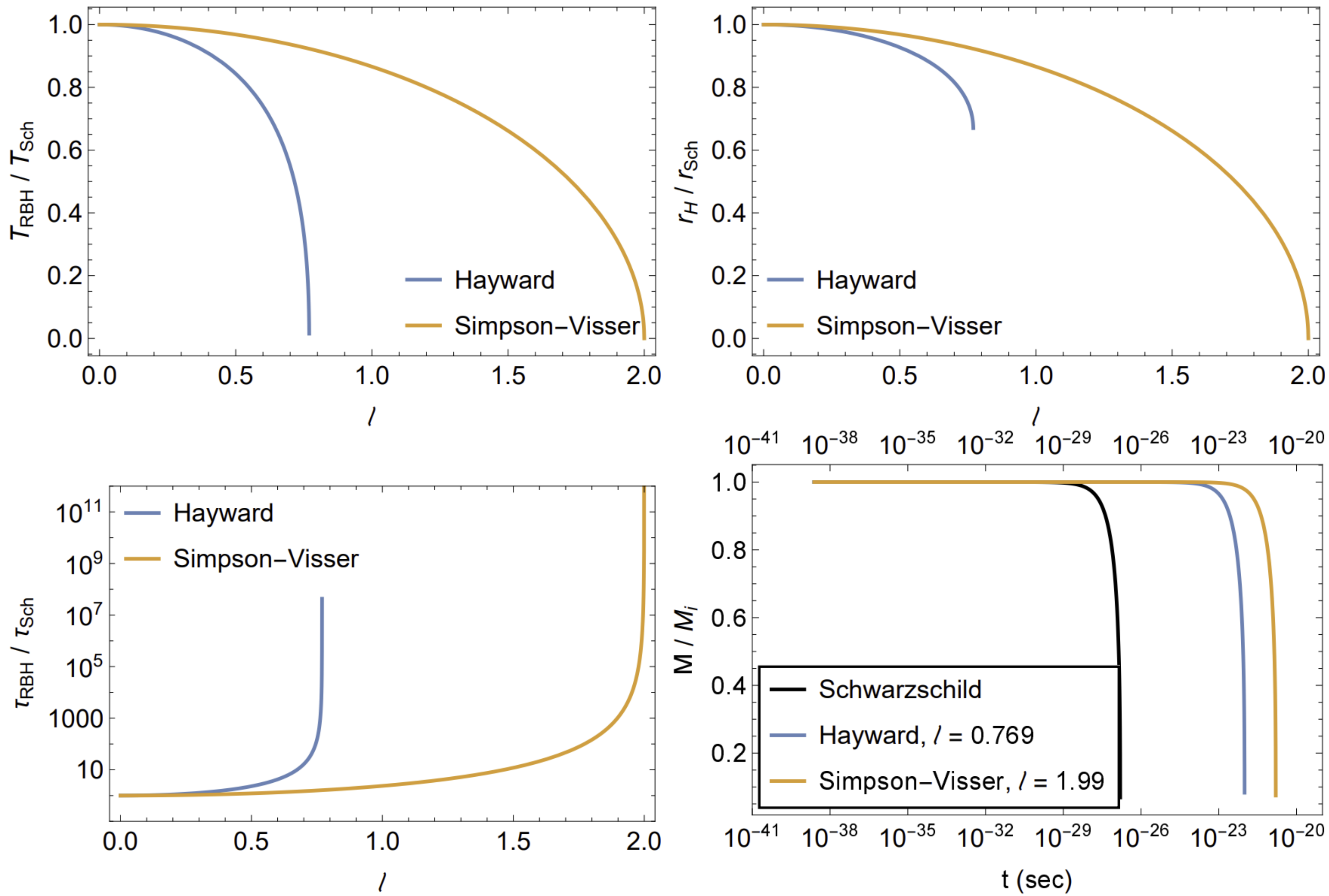
$$\left(\frac{M_i}{\mathrm{g}}\right) = 9.45 \times 10^{31} \gamma \left(\frac{106.75}{g_{*,i}}\right)^{1/2} \left(\frac{\mathrm{GeV}}{T_i}\right)^2,$$

$$\gamma \sim 1$$

$$\left(\frac{t_i}{\mathrm{sec}}\right) = 2.48 \times 10^{-39} \gamma^{-1} \left(\frac{M_i}{\mathrm{g}}\right).$$

$$\left(\frac{\tau}{\mathrm{sec}}\right) = 1.57 \times 10^{-27} \frac{1}{B(l)^2 A(l)^4} \left(\frac{106.75}{g_*(T_{\mathrm{H}})}\right) \left(\frac{M_i}{\mathrm{g}}\right)^3.$$

Properties of RPBHs



Cosmological constraints: 1. inflation

$$r < 0.1$$

$$\Rightarrow \quad \left(\frac{H_{\rm inf}}{\rm GeV}\right) < 7.82 \times 10^{13}.$$

$$\Downarrow$$

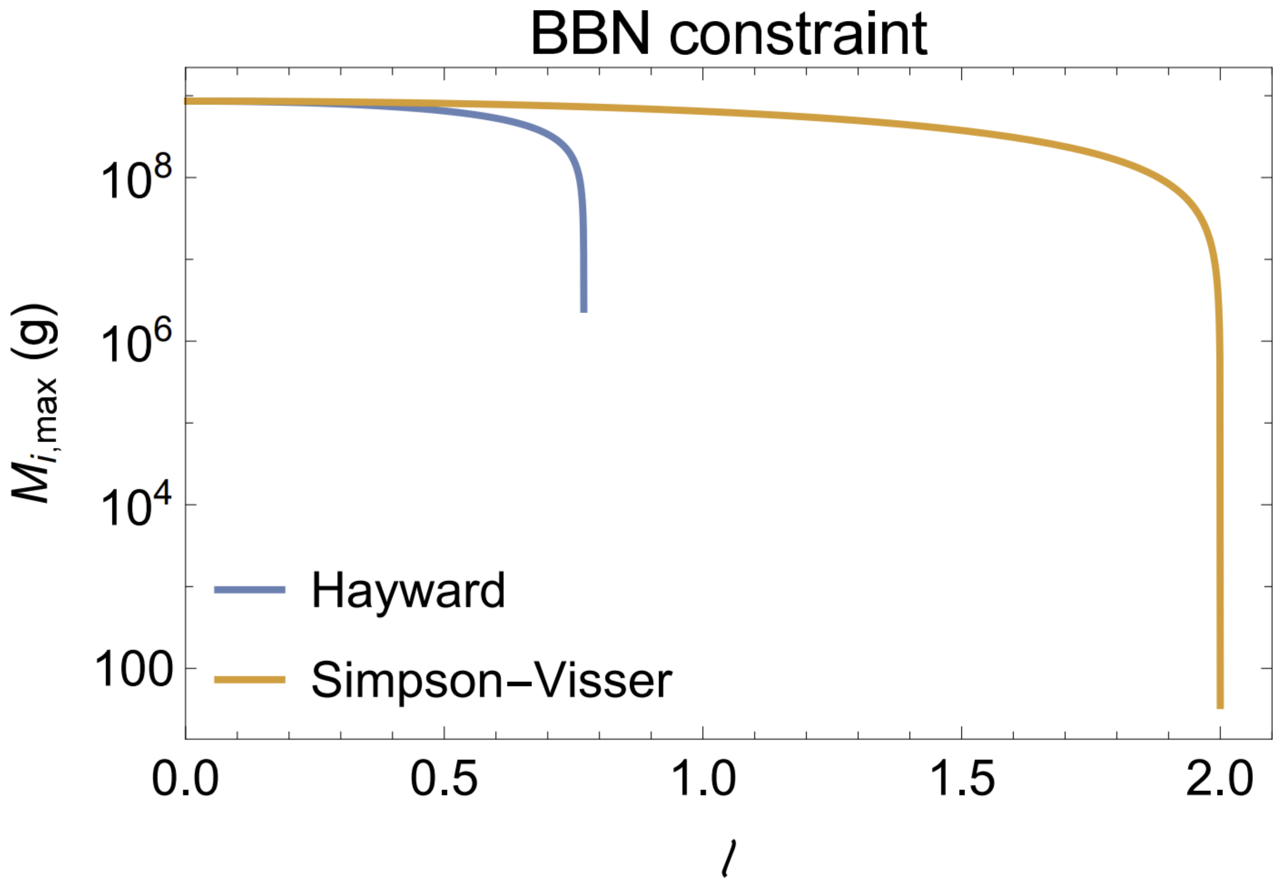
$$\left(\frac{T_{\rm reh}}{\rm GeV}\right) < 7.45 \times 10^{15},$$

$$\Leftarrow \quad \left(\frac{M_i}{\rm g}\right) > 1.7\ \gamma$$

Cosmological constraints: 2. BBN

$$\tau_{\rm RPBH} < 1 \ {\rm sec}$$

$$\left(\frac{M_i}{\rm g}\right) < 8.6 \times 10^8 A(l)^{4/3} B(l)^{2/3}.$$

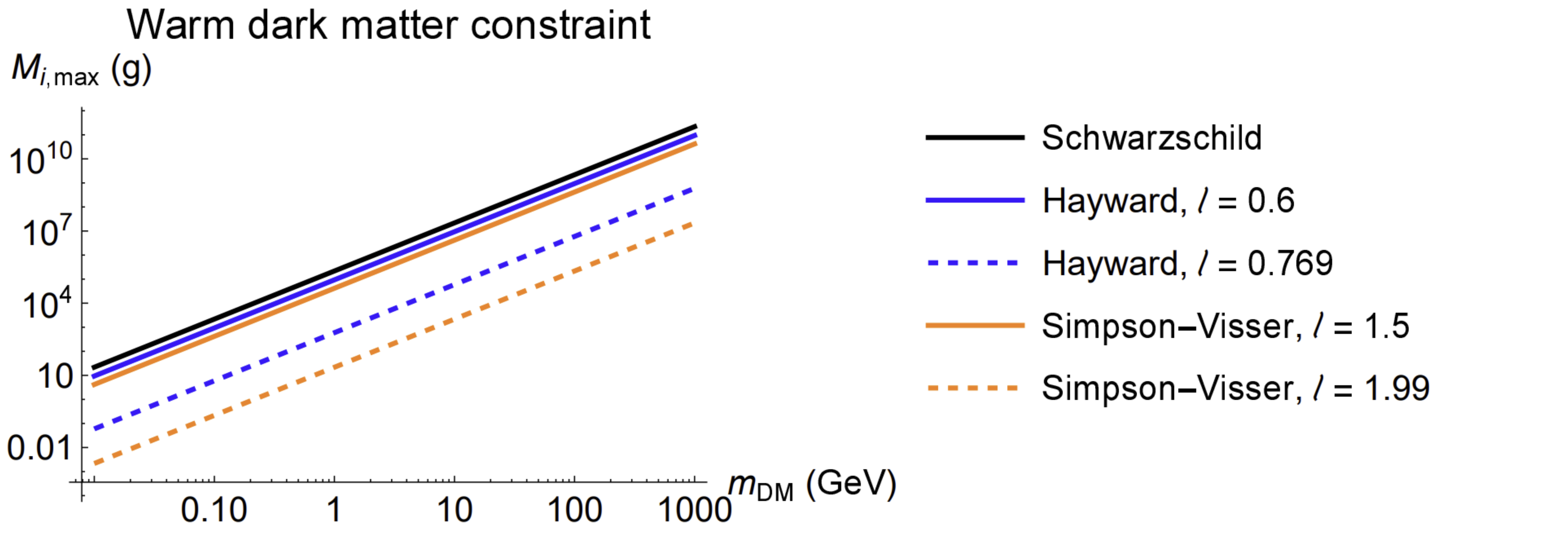


Cosmological constraints: 3. Warm DM

Must be cold by $T_\gamma \sim 1\ \mathrm{keV}$

$k \sim 10\ \mathrm{Mpc}^{-1}$

$$\left(\frac{M_i}{\mathrm{g}}\right) \lesssim 2.18 \times 10^5 A(l)^2 B(l)^2 \left(\frac{m_\chi}{\mathrm{GeV}}\right)^2 .$$



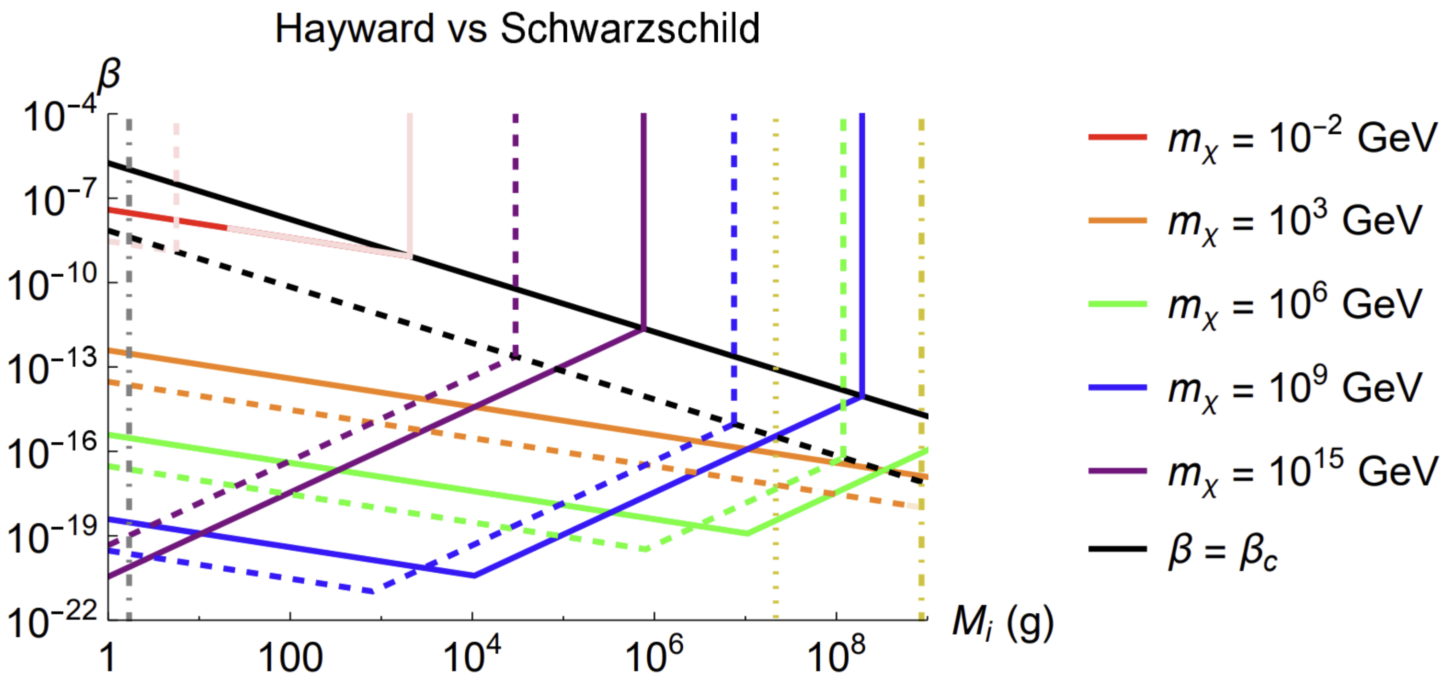
DM abundance

$$\beta_c = 1.78 \times 10^{-6} \gamma^{-1/2} A(l)^2 B(l) \left(\frac{\mathrm{g}}{M_i} \right)$$

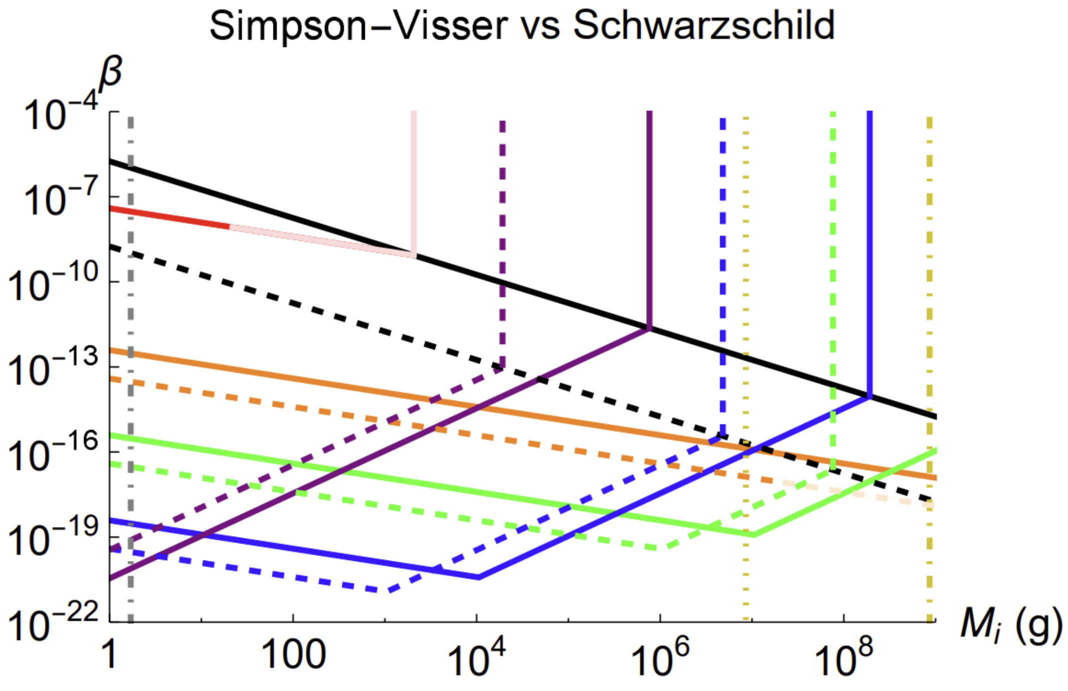
$$\beta(M) \equiv \frac{\rho_{\mathrm{PBH}}(t_{\mathrm{i}})}{\rho(t_{\mathrm{i}})}$$

1. If $\beta < \beta_c$:
   - If $T_{\mathrm{H,in}} > m_\chi$ $$\Omega_\chi \simeq 6.91 \times 10^{8} \gamma^{1/2} \frac{1}{A(l)} g_\chi \left(\frac{m_\chi}{\mathrm{GeV}} \right) \left(\frac{M_i}{\mathrm{g}} \right)^{1/2} \beta.$$
   - If $T_{\mathrm{H,in}} < m_\chi$ $$\Omega_\chi \simeq 7.74 \times 10^{34} \gamma^{1/2} A(l) g_\chi \left(\frac{\mathrm{GeV}}{m_\chi} \right) \left(\frac{\mathrm{g}}{M_i} \right)^{3/2} \beta.$$
2. If $\beta \geq \beta_c$:
   - If $T_{\mathrm{H,in}} > m_\chi$ $$\Omega_\chi \simeq 1229 A(l) B(l) g_\chi \left(\frac{m_\chi}{\mathrm{GeV}} \right) \left(\frac{\mathrm{g}}{M_i} \right)^{1/2}$$
   - If $T_{\mathrm{H,in}} < m_\chi$ $$\Omega_\chi \simeq 1.38 \times 10^{29} A(l)^3 B(l) g_\chi \left(\frac{\mathrm{GeV}}{m_\chi} \right) \left(\frac{\mathrm{g}}{M_i} \right)^{5/2}$$

DM abundance



$l = 0.769$



$l = 1.99.$

Conclusion

- We presented a scenario of particle DM production from evaporation of ultra-light self-similar RPBHs.

- Cosmological constraints and parameter space to obtain correct DM abundance could be shifted by orders of magnitude

- Many potential further developments:
  - Extended mass function
  - Spinning RPBHs
  - Observational channels such as GW