Pathways for primordial black holes to resolve the dark matter problem

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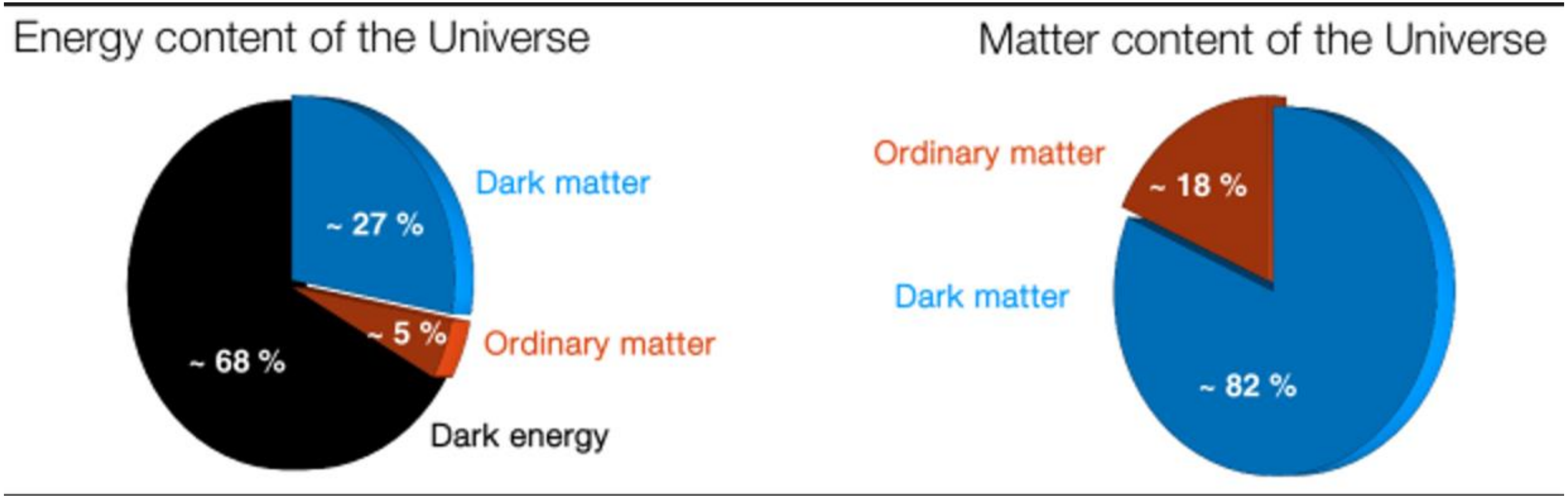
Mainly based on :

- Loc, EPJC, 2026
- Loc, PRD,2025
- Loc, [2512.04548]

Outline

1. The dark matter (DM) problem
2. The big picture of primordial black holes (PBHs)
3. PBHs can resolve the DM problem in two ways:
   - Particle DM is produced from Hawking evaporation of ultra-light PBHs
   - Heavy PBHs themselves can be a DM candidate in the "asteroid-mass window"
4. Summary

1. The DM problem

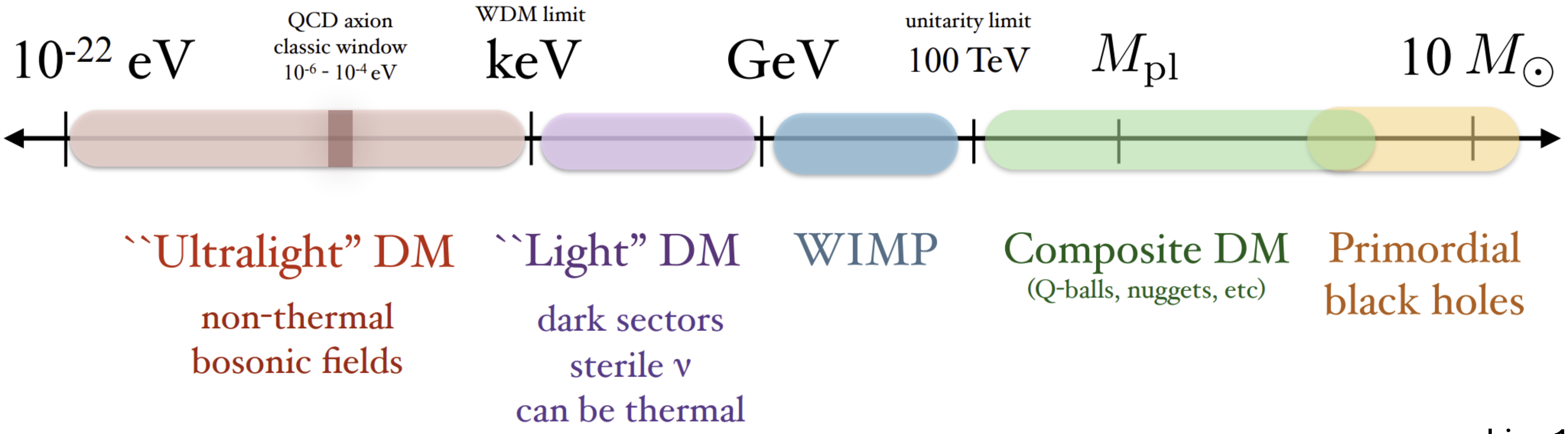


What is the nature of Dark Matter?

How can we obtain the correct DM relic abundance?

Generic properties of DM

- Cold
- Weak couplings with SM particles
- Collisionless among themselves
- Stable
- Should be produced prior to BBN (not strictly necessary)



Lin, 1904.07915

2. The big picture of primordial black holes (PBHs)

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 ~0.00001 g to ~ 100 000 solar masses.

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

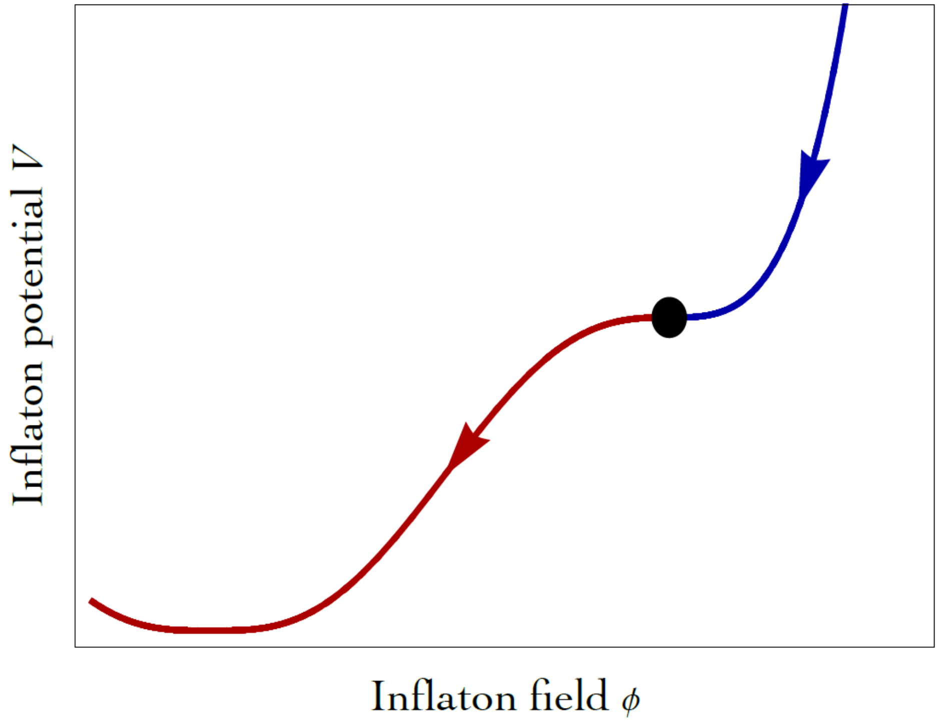
How PBHs are formed
Example 1. Inflationary perturbations

$$M_{\mathrm{PBH,i}} \simeq \gamma M_{\mathrm{H,i}}$$

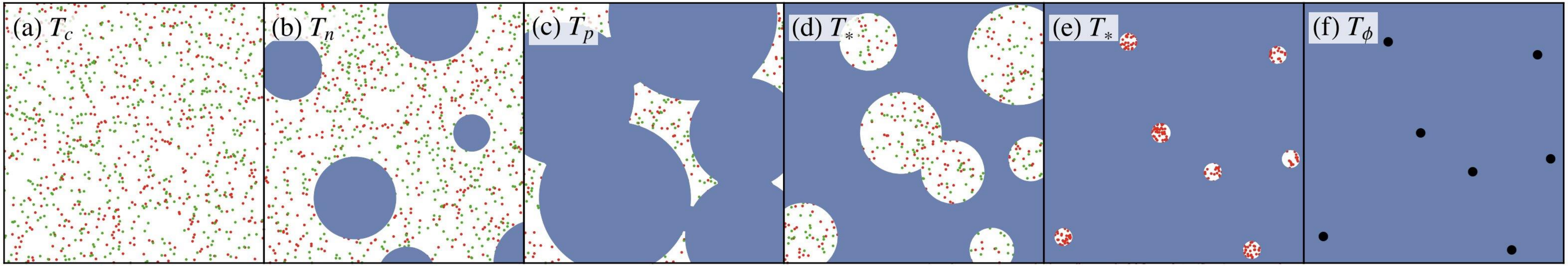
$$\left(\frac{M_{\mathrm{PBH,i}}}{\mathrm{g}}\right) \approx 1.89 \times 10^{31} \left(\frac{\gamma}{0.2}\right)\left(\frac{106.75}{g_{\rho,\mathrm{i}}}\right)^{1/2}\left(\frac{\mathrm{GeV}}{T_{\mathrm{i}}}\right)^{2}.$$

$$\beta(M) \equiv \frac{\rho_{\mathrm{PBH}}(t_{\mathrm{i}})}{\rho(t_{\mathrm{i}})} \qquad \beta_i \propto \exp(-P_\zeta^{-1})$$

$$P_\zeta \approx V/24\pi^2 \bar{M}_{\mathrm{Pl}}^4 \epsilon$$



How PBHs are formed
Example 2. Collapse of Fermi balls in a FOPT



$$\mathcal{L} = -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - U(\phi) + \bar{\chi}i\partial\!\!\!/\chi - g_\chi\phi\bar{\chi}\chi$$

$$g_\chi w_* \gg T_*$$

$$V(r) = -\frac{g_\chi^2}{4\pi r}e^{-M_\phi r}$$

$$M_{\mathrm{PBH,i}} \approx 1.4\times 10^{21}\mathrm{g}\ v_w^3\left(\frac{\eta_\chi}{10^{-3}}\right)\left(\frac{100}{g_*}\right)^{1/4}\left(\frac{100\ \mathrm{GeV}}{T_*}\right)^2\left(\frac{100}{\beta/H_*}\right)^3\alpha_*^{1/4}$$

$$M_\phi^2 = \frac{d^2U(\phi,T)}{d\phi^2}\Big|_{\phi=0} = \mu^2 + cT^2,$$

$$L_\phi \sim R_{\mathrm{FB}}Q_{\mathrm{FB}}^{-1/3}$$

$$\beta'_{\mathrm{PBH,i}} \approx 1.4\times 10^{-15}v_w^{-3}\left(\frac{g_*}{100}\right)^{1/2}\left(\frac{T_*}{100\ \mathrm{GeV}}\right)^3\left(\frac{\beta/H_*}{100}\right)^3\left(\frac{M_{\mathrm{PBH,i}}}{10^{15}\mathrm{g}}\right)^{3/2}.$$

Kawana and Xie, PLB (2022)

3. PBHs can resolve the DM problem in two ways:

#1 Particle DM is produced from Hawking evaporation of ultra-light PBHs

#2 Heavy PBHs as DM

#1 Particle DM is produced from Hawking evaporation of ultra-light PBHs

Static, spherically symmetric PBHs

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

$$f_{\rm Hay}(r) = g_{\rm Hay}(r) = 1 - \frac{2(r/GM)^2}{(r/GM)^3 + 2l^2}, \qquad h_{\rm Hay}(r) = r^2$$

$$f_{\rm SV}(r) = g_{\rm SV}(r) = 1 - \frac{2}{\sqrt{(r/GM)^2 + l^2}}, \qquad h_{\rm SV}(r) = (GM)^2\left[\left(\frac{r}{GM}\right)^2 + l^2\right],$$

Loc, arXiv: 2510.09395 , EPJC (2026)

Evaporation of PBHs

$f(r) = 0 \Rightarrow r_H$

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

$$A(l) \equiv \frac{T_{\mathrm{H}}}{T_{\mathrm{Sch}}}; \qquad B(l) \equiv \frac{R_{\mathrm{H}}}{r_{\mathrm{Sch}}} = \frac{\sqrt{h(r_{\mathrm{H}})}}{r_{\mathrm{Sch}}}.$$

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

Loc, arXiv: 2510.09395 , EPJC (2026)

Properties of PBHs

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

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

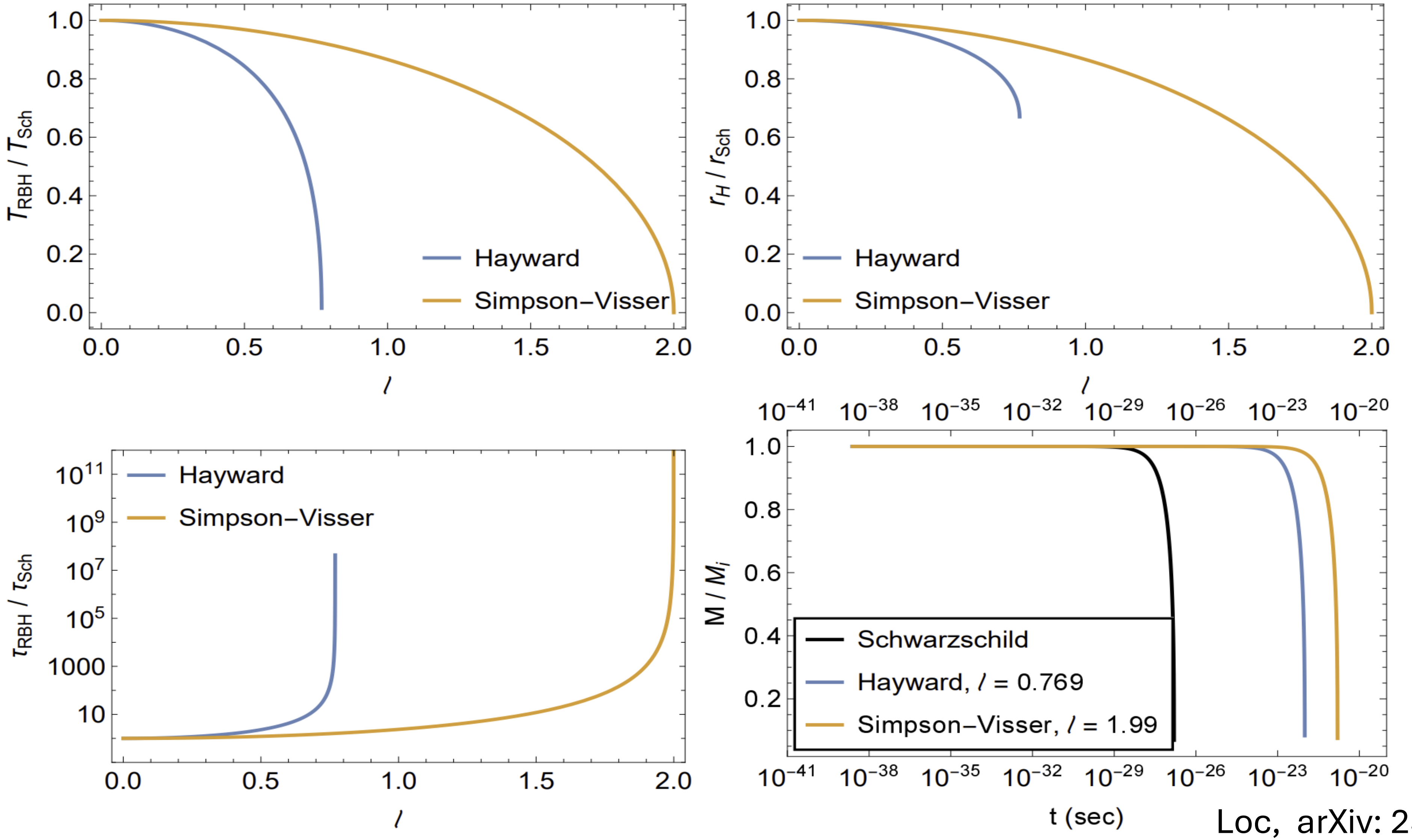
$$\gamma \sim 1$$

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

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

Loc, arXiv: 2510.09395 , EPJC (2026)

Properties of PBHs



Loc, arXiv: 2510.09395 , EPJC (2026)

Cosmological constraints: 1. inflation

$$r < 0.1 \quad \Longrightarrow \quad \left(\frac{H_{\rm inf}}{\rm GeV}\right) < 7.82 \times 10^{13}.$$

$$\Downarrow$$

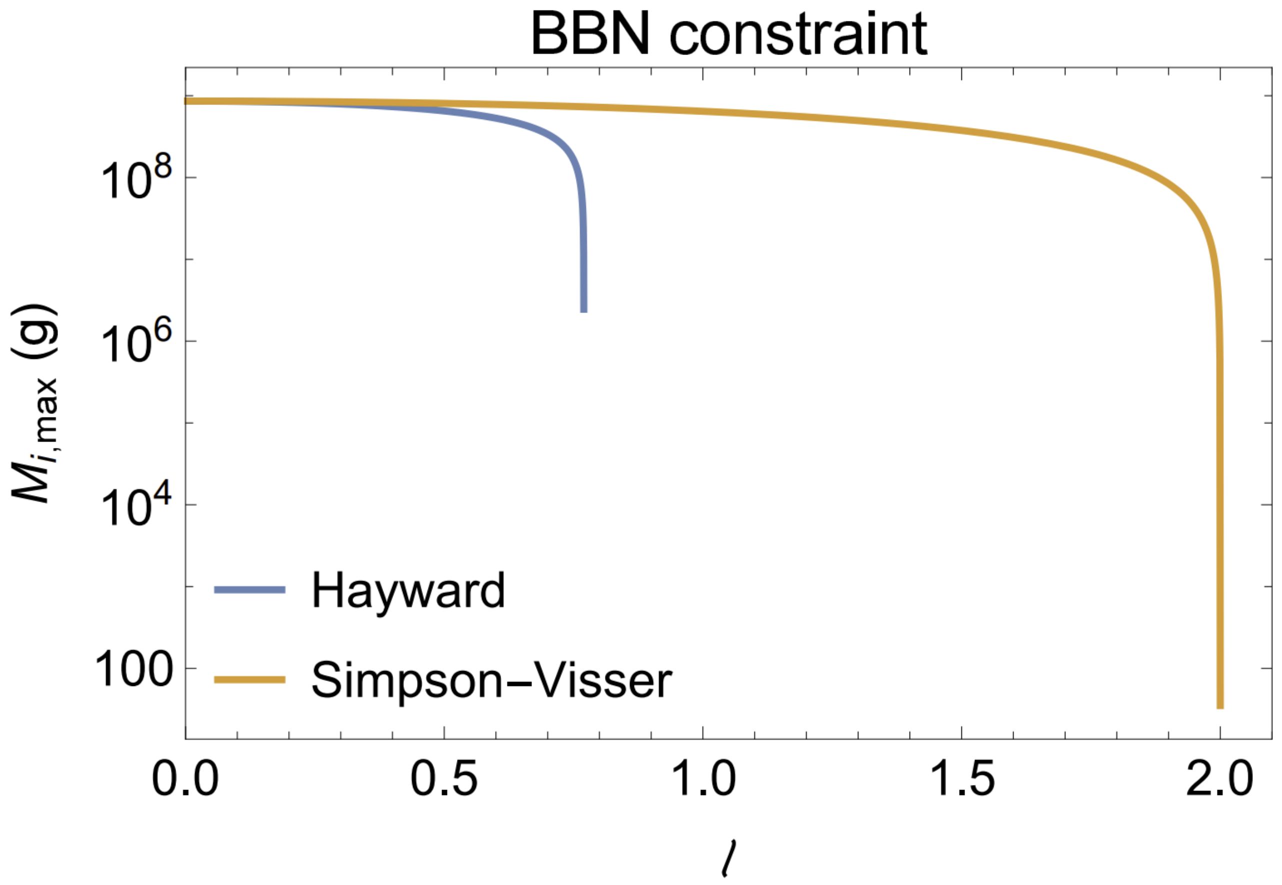
$$\left(\frac{M_i}{\rm g}\right) > 1.7\ \gamma \quad \Longleftarrow \quad \left(\frac{T_{\rm reh}}{\rm GeV}\right) < 7.45 \times 10^{15},$$

Loc, arXiv: 2510.09395 , EPJC (2026)

Cosmological constraints: 2. BBN

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

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



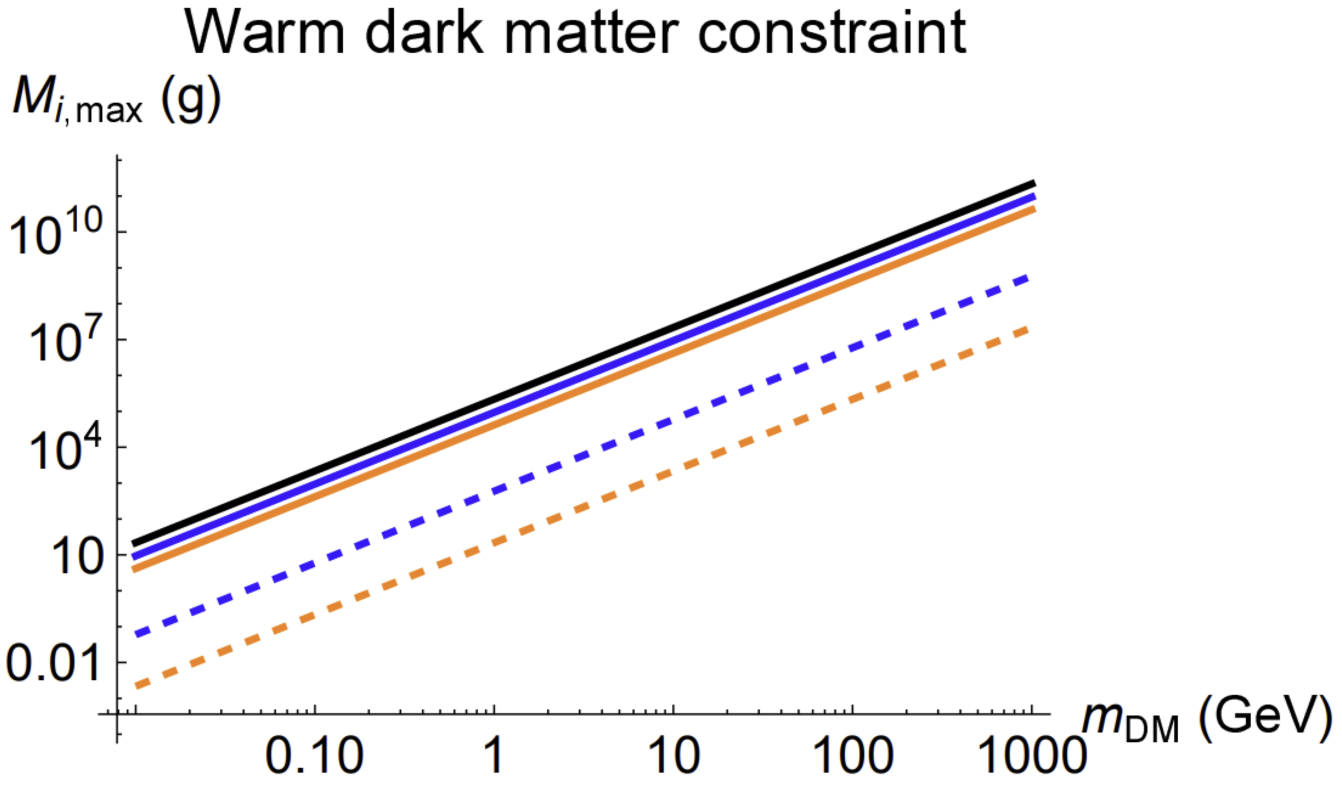
Loc, arXiv: 2510.09395 , EPJC (2026)

Cosmological constraints: 3. Warm DM

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

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

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



Loc, arXiv: 2510.09395 , EPJC (2026)

Loc, arXiv: 2510.09395 , EPJC (2026)

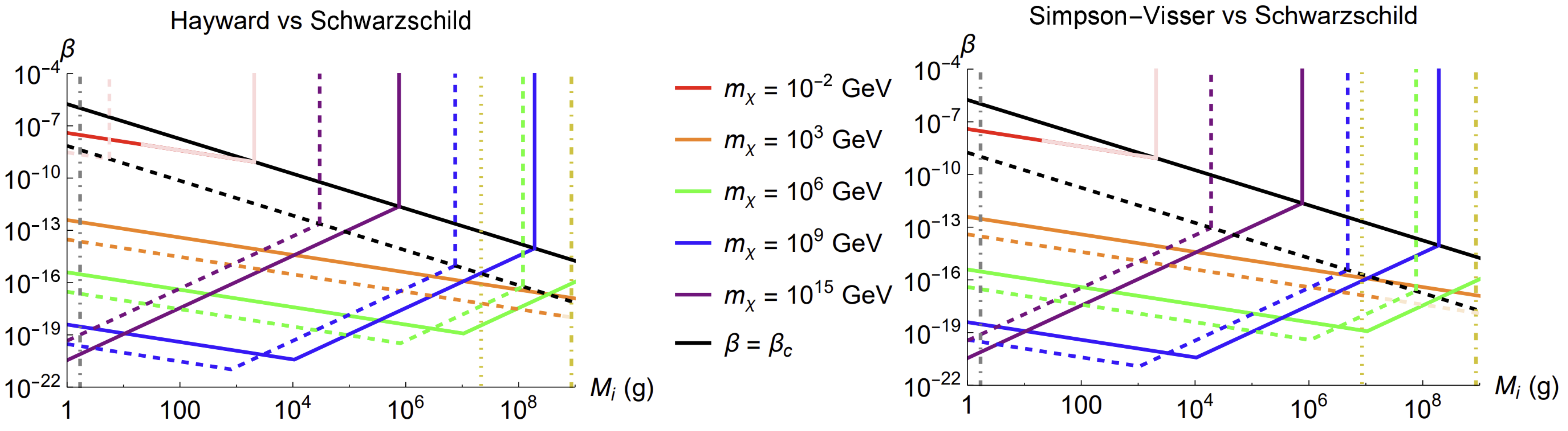
DM abundance

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

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

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

DM abundance



$l = 0.769$

$l = 1.99.$

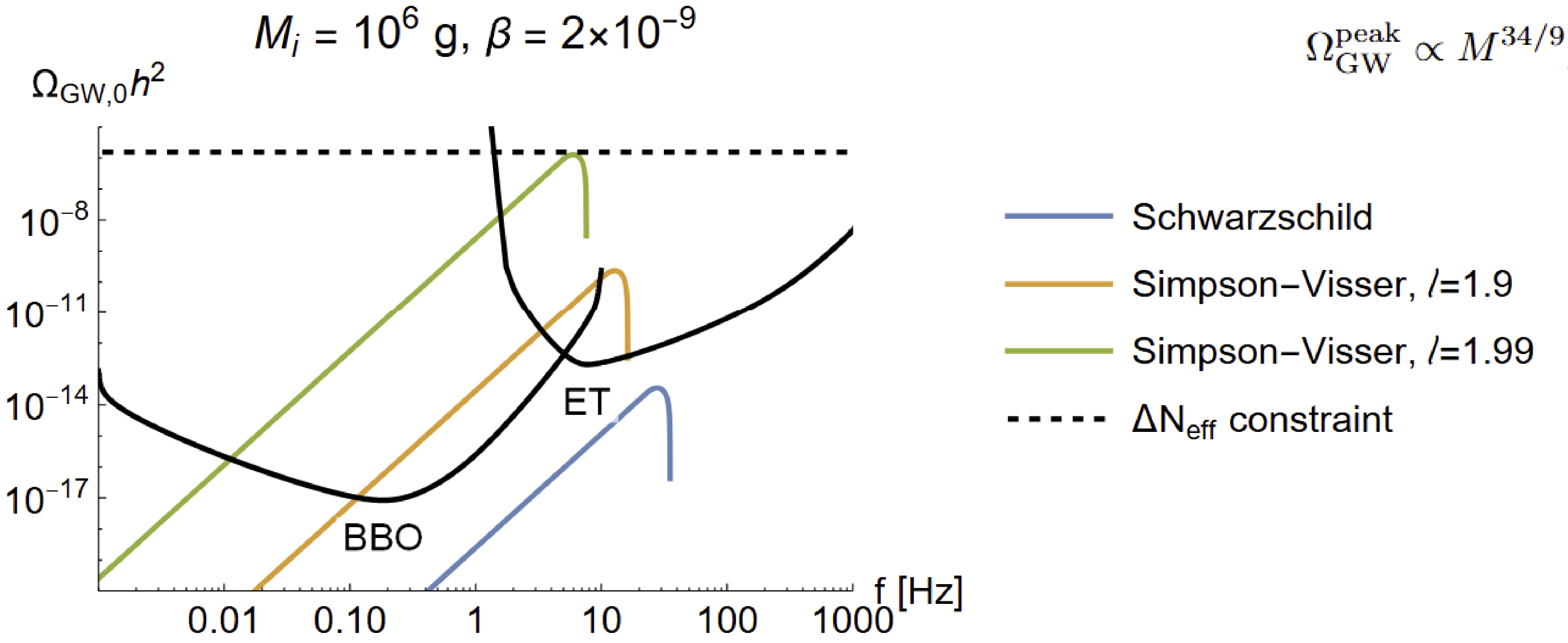
Loc, arXiv: 2510.09395 , EPJC (2026)

GW from isocurvature perturbation

$$\Omega_{\rm GW}(f) \propto f^{11/3}$$

$$f_{\rm peak} \propto M^{-5/6}$$

$$\Omega_{\rm GW}^{\rm peak} \propto M^{34/9}\beta^{16/3}$$

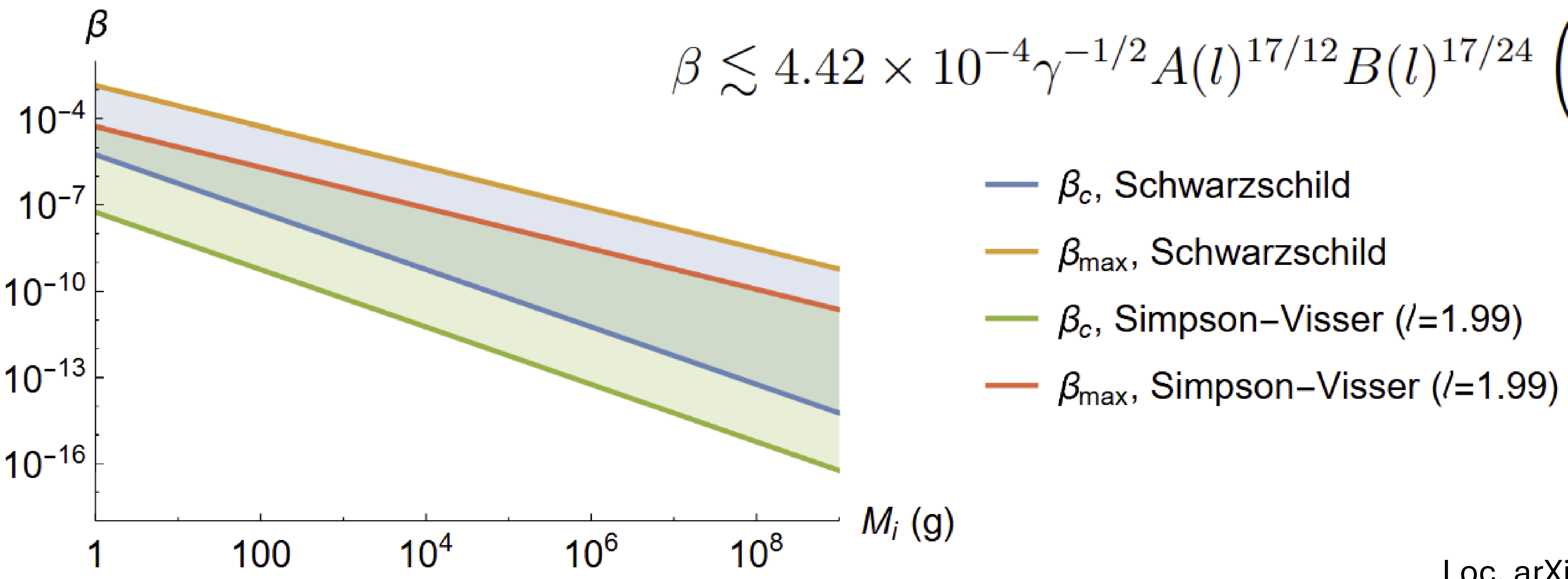


Loc, arXiv: 2512.04548

Constraint on ultra-light PBH

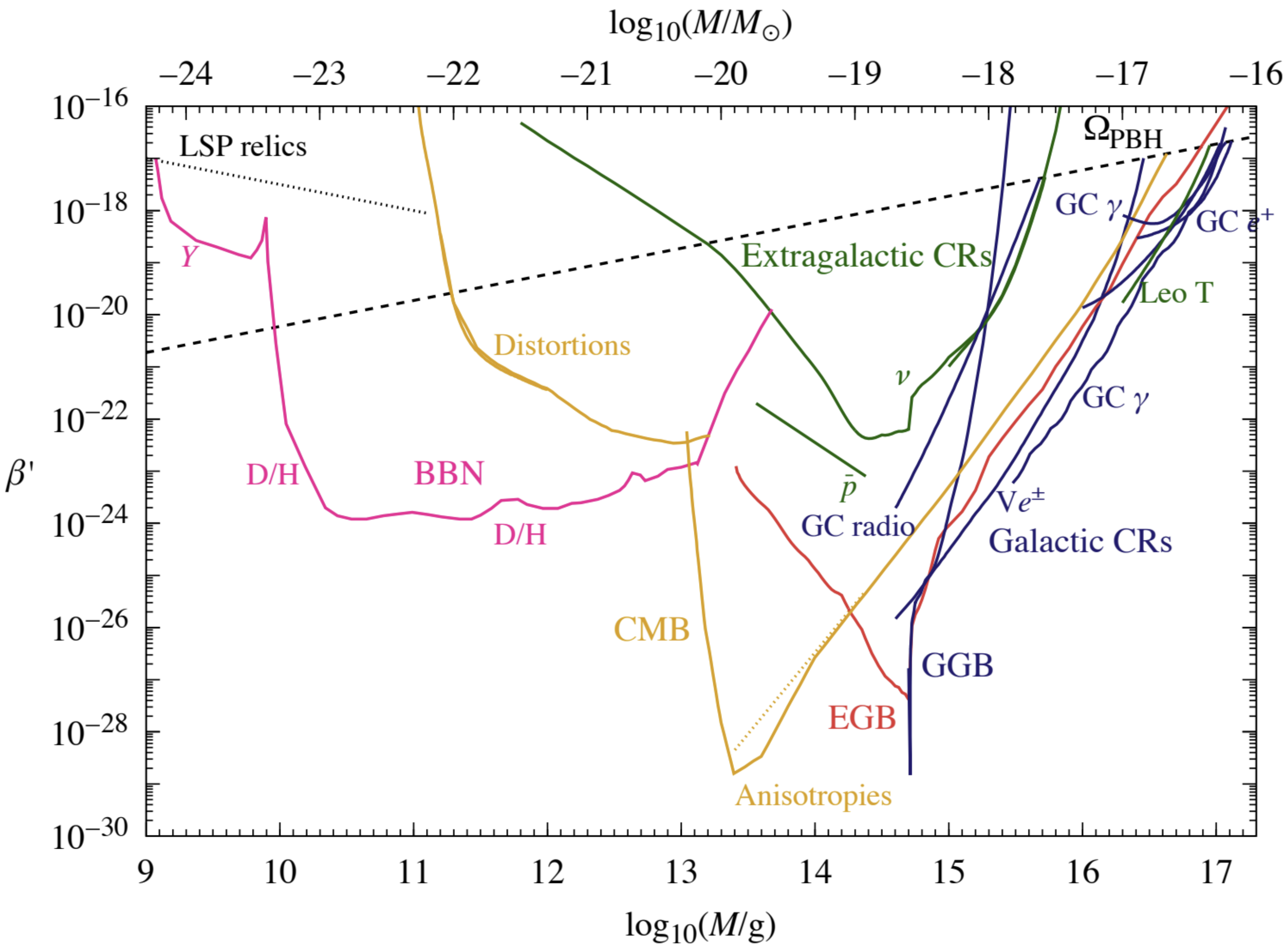
$$\Delta N_{\rm eff} < 0.3 \Rightarrow \Omega^{\rm tot}_{\rm GW,0} < 3.45 \times 10^{-6}$$

$$\beta \lesssim 4.42 \times 10^{-4} \gamma^{-1/2} A(l)^{17/12} B(l)^{17/24} \left(\frac{\rm g}{M_i}\right)^{17/24} ,$$



Loc, arXiv: 2512.04548

Constraint on Light PBHs



[2002.12778]

#2 Heavy PBHs as DM

Constraints on heavy PBHs

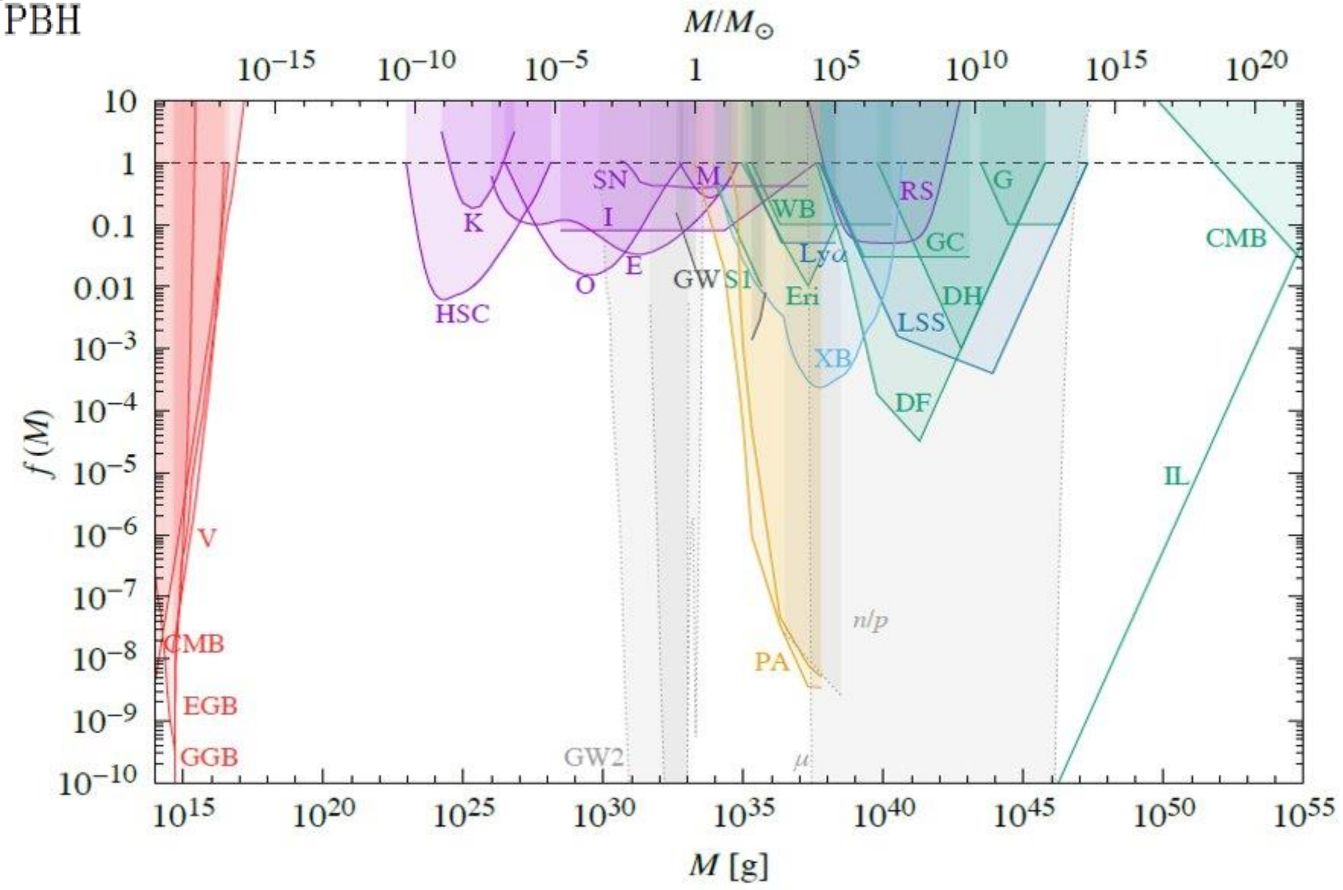
$$\beta_{\rm PBH,i} \simeq 6\times 10^{-26}\left(\frac{g_{\rho,\rm i}}{106.75}\right)^{1/4}\gamma^{-1/2}\left(\frac{M_{\rm PBH}}{\rm g}\right)^{1/2} f_{\rm PBH}$$

$$10^{17}\ \mathrm{g} \lesssim \mathrm{M_i} \lesssim 10^{23}\ \mathrm{g}$$

$$f \equiv \Omega_{\rm PBH}/\Omega_{\rm DM}.$$

$$10^{-21}\ \mathrm{s} \lesssim \mathrm{t_i} \lesssim 10^{-15}\ \mathrm{s}$$

$$10^{4}\ \mathrm{GeV} \lesssim \mathrm{T_i} \lesssim 10^{7}\ \mathrm{GeV}$$



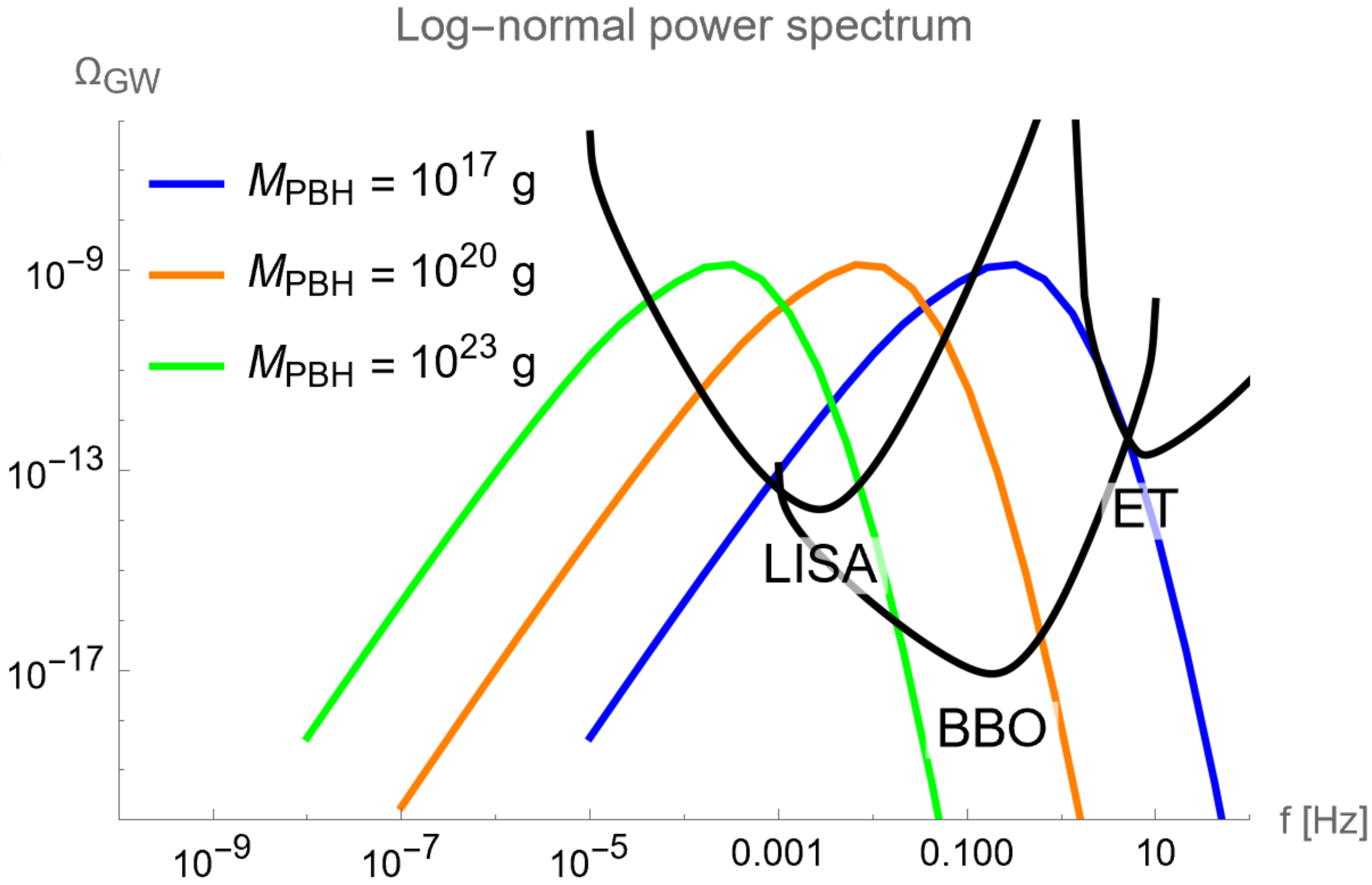
[2002.12778]

SIGW from PBH formation

$$\Omega_{\rm GW} \propto \mathcal{P}_h \propto \int dk dk' \, \mathcal{P}_\zeta(k) P_\zeta(k')$$

$$P_\xi(k) = \frac{A}{\sqrt{2\pi\sigma^2}} \exp\left[-\frac{\ln^2(k/k_p)}{2\sigma^2}\right],$$

$$f_{\rm peak,inf} \propto M_{\rm PBH}^{-1/2}$$



Use the framework of Loc, arXiv: 2410.17544 , PRD, 2025

Summary

- DM is a major contribution to the energy content of the Universe and is the reason why we are here, but so far has escaped all attempted direct detection!

- Particle DM can be produced from Hawking evaporation of ultra-light PBHs, but a region of parameter space is constrained from GW of isocurvature perturbation

- Heavy PBHs in the "asteroid-mass window" can also be a natural DM candidate with predictive GW signals that could be within the reach of near-future GW detectors


Thank you and take care!