Recycled Dark Matter

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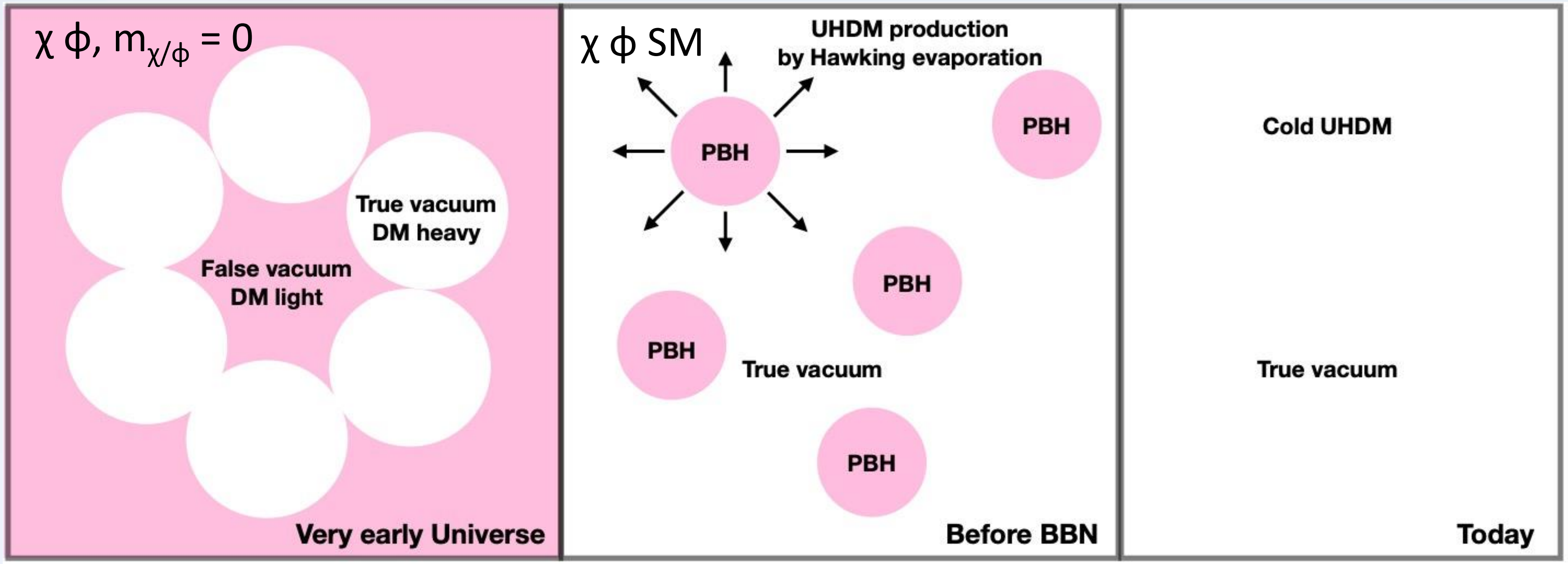
arXiv: 2310.08526

Outline of Talk

- Overall story of recycled dark matter
- Trapped (Multicomponent Dark Sector)
- PBH formation
- UHDM produced from PBHs

History of PBH Formation



- First order phase transition (FOPT) caused by symmetry breaking of a scalar ϕ

1. Multicomponent heavy dark sector (DS) is trapped because mass is too high to penetrate the bubble wall
2. Trapped Multicomponent Dark Sector becomes compressed until PBHs form
    - Mininmum size of pocket therefore PBH mass due to annihilation of Dark matter leads to extended mass function being controlled by IR physics
3. Light PBHS Hawking evaporated recycled ultra heavy dark matter (UHDM) before BBN
4. Dark sector satisfies the observed dark matter relic abundance

Trapped Dark Sector During FOPT

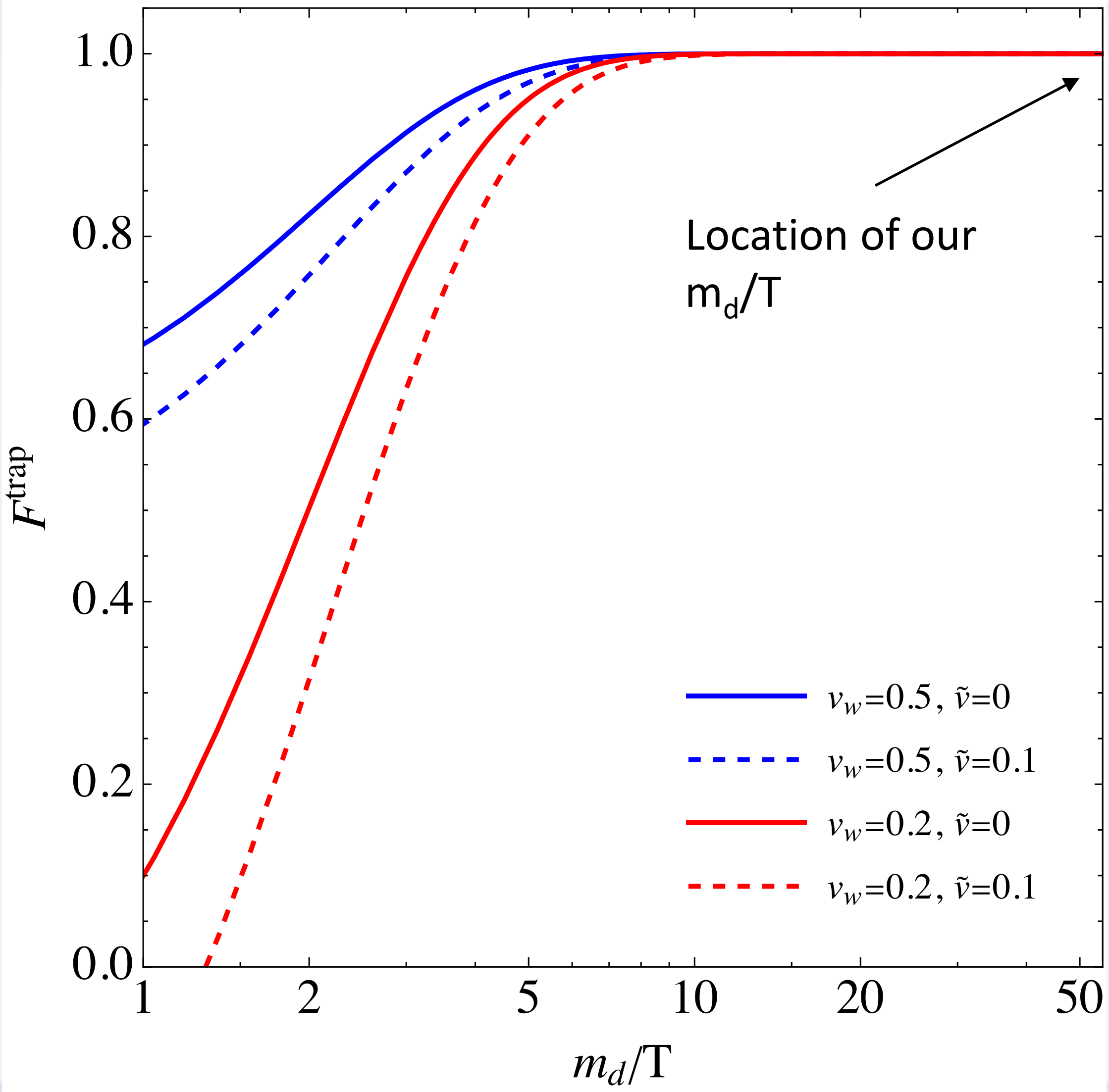
$$\frac{\Delta N_{\rm in}}{\Delta A} = \frac{g_d}{(2\pi)^3}\int d^3\vec{p}\int_{r_o}^{r_0-\frac{p_z\Delta t}{|\vec{p}|}} dr\,\mathcal{T}(\vec{p})\,\Theta(-p_z)\,f(\vec{p};\vec{x})$$

$$J_w = \frac{g_d T^3\,(1+\tilde{\gamma}\,m_d\,(1-\tilde{v})/T)}{4\,\pi^2\,\tilde{\gamma}^3\,(1-\tilde{v})^2}\,e^{-\tilde{\gamma}\,m_d\,(1-\tilde{v})/T}.$$

$$n_d^{\rm filtered} = \frac{J_w}{\gamma_w\,v_w}$$

$$F^{\rm trap} = 1 - n_d^{\rm filtered}/n_d$$

- The probability of a DM particle penetrating through the moving bubble wall is given by J_w. The probability of being trapped in false vacuum is given by F^{trapped}
- tildes are in the bubble wall rest frame. Quantities without tildes are in the global plasma rest frame
- The greatest suppression to trapping is in the exponential which is controlled by dark matter mass and particle temperature



Thermal History

$$\chi + \bar{\chi} \to \text{SM} + \text{SM}$$

$$\mathcal{L}_{\text{SM-DS}} = \frac{\alpha_\Lambda}{\Lambda}\bar{\chi}\chi H^\dagger H$$

$$\alpha_\Lambda \gtrsim 0.17 \times \left(\frac{g_\star}{106.75 + 4.5}\right)^{1/4} \left(\frac{\Lambda}{10^{16}\ \text{GeV}}\right)^{1/2}$$

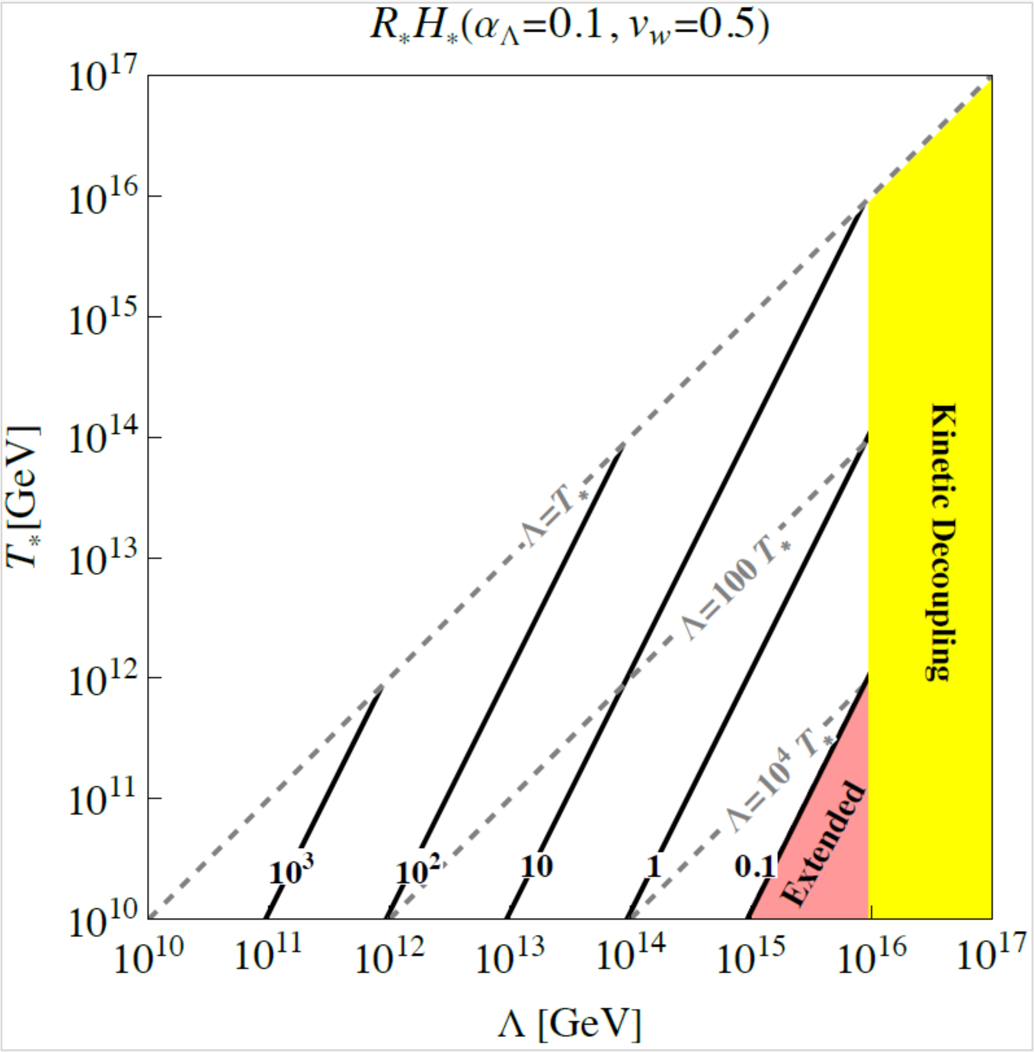
Lower bound to maintain kinetic equilibrium with SM

When T < Λ the cross section is a constant

$$\Gamma_{\text{ann}} = n_\chi \frac{\alpha_\Lambda^2}{\Lambda^2} \qquad n_\chi = \frac{3}{4}\frac{\zeta(3)}{\pi^2} g_\chi \left(\frac{R_\star}{R(t)}\right)^3 T_\star^3$$

$$\Gamma_{\text{ann}} \times t_c < 1$$

$$R_\star > 0.27\, H_\star^{-1} \left(\frac{\alpha_\Lambda}{0.1}\right)\left(\frac{0.5}{v_w}\right)^{1/2}\left(\frac{T_\star}{\Lambda}\right)\left(\frac{M_{\text{pl}}}{T_\star}\right)^{1/2}$$



PBH Formation

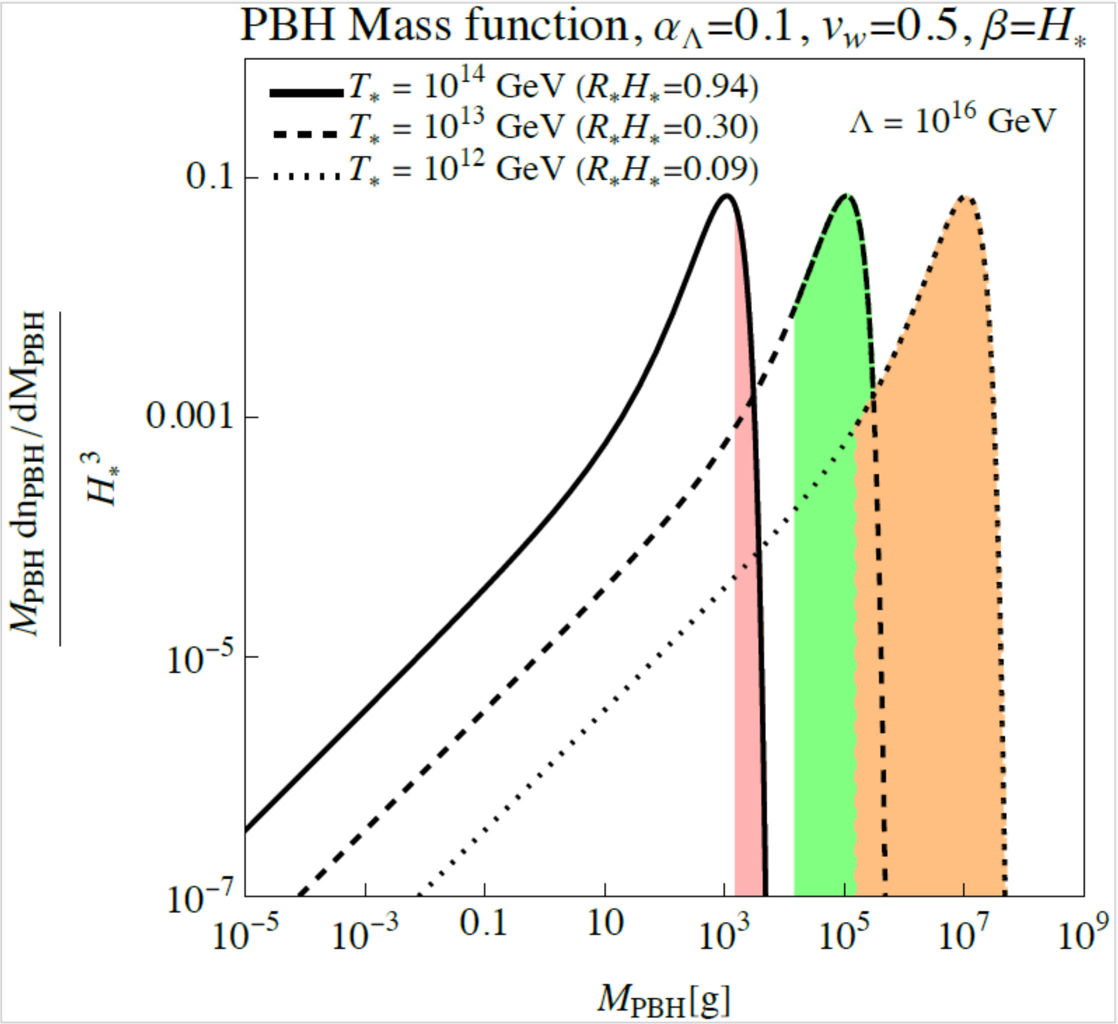
$$M_{\rm PBH} = \left[\frac{2\pi^3}{90}\left(g_\phi + \frac{7}{8}g_\chi\right)\right]^{1/2} R_\star^2 T_\star^2 M_{\rm Pl}$$

Include lower bound due to annihilation in small pockets

$$R_\star > 0.27\, H_\star^{-1} \left(\frac{\alpha_\Lambda}{0.1}\right)\left(\frac{0.5}{v_w}\right)^{1/2}\left(\frac{T_\star}{\Lambda}\right)\left(\frac{M_{\rm pl}}{T_\star}\right)^{1/2}$$

$$\frac{dn_{\rm PBH}}{dM_{\rm PBH}} \simeq \frac{I_\star^4\,\beta^4 M_{\rm PBH}^{-1/2}}{384\,T_\star\, v_w^3 \left(\frac{2\pi^3}{90G}\left(g_\phi + \frac{7}{8}g_\chi\right)\right)^{1/4}} e^{4\beta R_\star/v_w - I_\star e^{\beta R_\star/v_w}}\left(1 - e^{-I_\star e^{\beta R_\star/v_w}}\right)$$

$$\times\Theta\left(M_{\rm PBH} - 6.9\times 10^{-3}\sqrt{g_\phi + \frac{7}{8}g_\chi}\,\frac{\alpha_\Lambda^2}{v_w}\frac{M_{\rm Pl}^4}{T_\star\Lambda^2}\right)$$



PBH Evaporation & DM Relic Abundance

Total number of DM = (Number of DM from PBHs) x (Total number of PBHs)

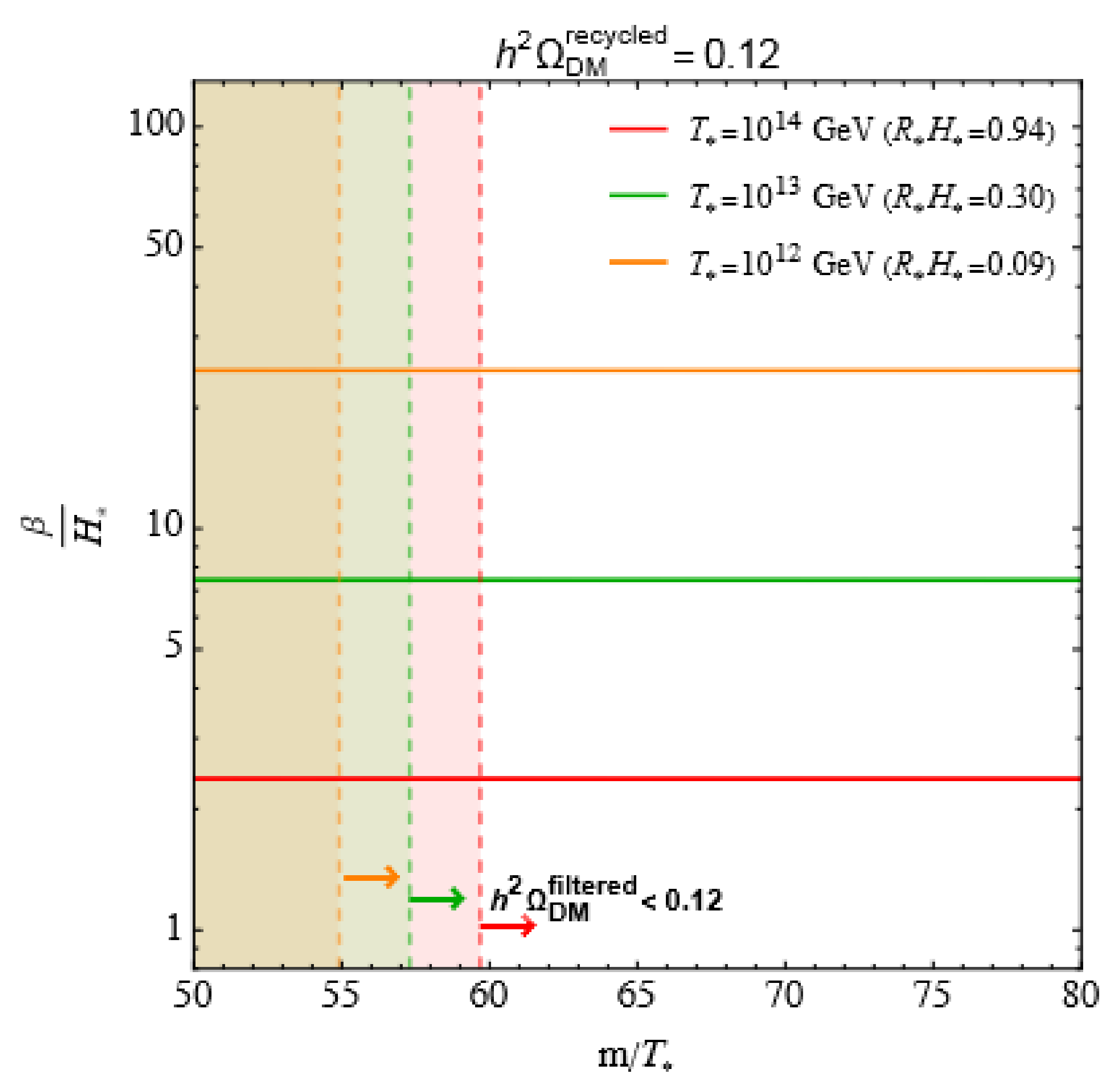
$$N_i = \frac{120\,\zeta(3)}{\pi^3}\frac{g_i}{g_\star(T_{\rm PBH})}\frac{M_{\rm PBH}^2(t_\star)}{M_{\rm Pl}^2}, \qquad T_{\rm PBH}(t_\star) > m_i,$$

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

$$Y_{\rm DM} = \frac{3}{4}\beta_{\rm PBH}N_{\rm DM}\frac{T_\star(M_{\rm PBH})}{M_{\rm PBH}}$$

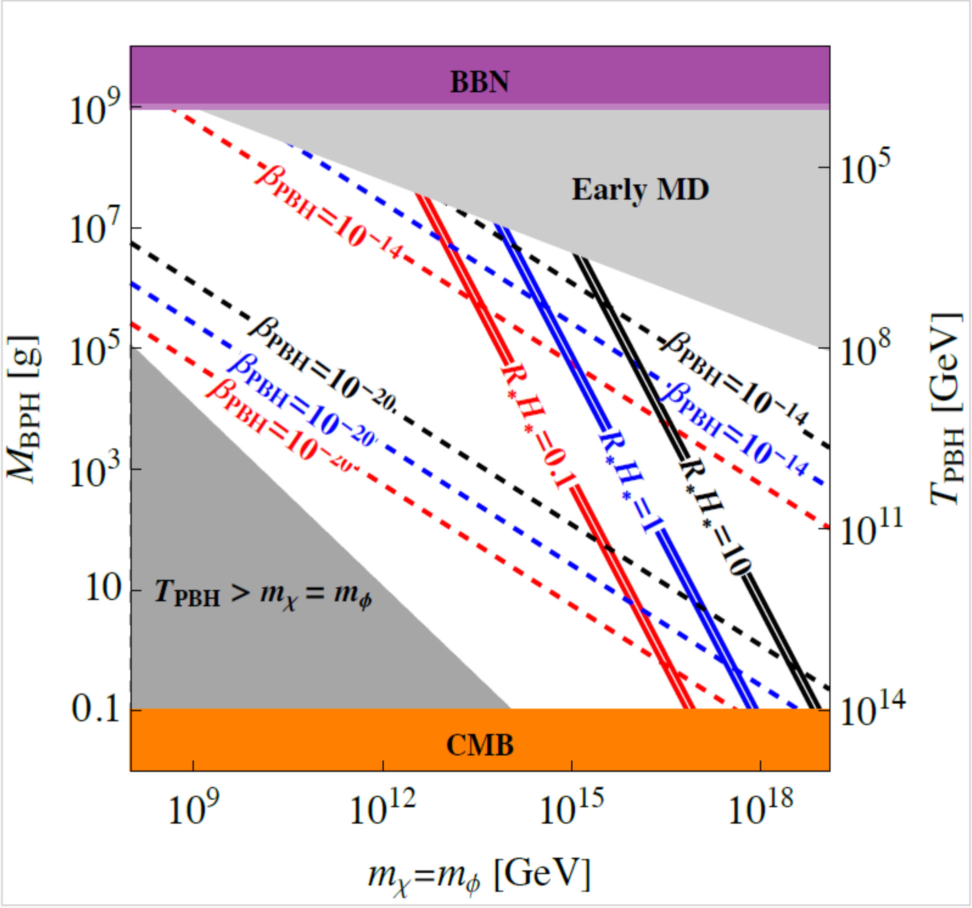
$$\Omega_{\rm DM} = \frac{\rho_{\rm DM}(t_0)}{\rho_c} = \frac{m_{\rm DM}Y_{\rm DM}}{\rho_c}s(t_0)$$

$$\Omega_{DM} = \frac{45\sqrt{3}\times 5^{1/4}\zeta(3)}{16\times 2^{1/4}\pi^{23/4}}\frac{(3g_\chi+4g_\phi)(7g_\chi+8g_\phi)^{1/4}}{(8g_\star+7g_\chi+8g_\phi)^{3/2}}\beta_{\rm PBH}\frac{R_\star}{H_\star^{-1}}\frac{s(t_0)}{m\rho_c}\frac{M_{\rm Pl}^{7/2}}{M_{\rm PBH}^{3/2}}$$



UHDM from PBHs Formed by a Trapped Dark Sector

$$\Omega_{DM} = \frac{45\sqrt{3}\times 5^{1/4}\zeta(3)}{16\times 2^{1/4}\pi^{23/4}}\frac{(3g_\chi+4g_\phi)(7g_\chi+8g_\phi)^{1/4}}{(8g_\star+7g_\chi+8g_\phi)^{3/2}}\beta_{\rm PBH}\frac{R_\star}{H_\star^{-1}}\frac{s(t_0)}{m\rho_c}\frac{M_{\rm Pl}^{7/2}}{M_{\rm PBH}^{3/2}}$$



Summary

- Multicomponent DS is trapped during FOPT and collapses into PBH. The same UHDM is reproduced (Recycled) by Hawking evaporation of PBHs and matches observed relic abundance.
- Annihilation of DM to SM particles controls the PBH mass function.
- Recycling mechanism can be tested GWs in the MHz-GHz range

Recycled Dark Matter: arXiv: 2310.08526

T. Gehrman, B. Es Haghi, K. Sinha, T. Xao

PBH+Baryogensis+HFGWs: arXiv:2211.08431

PBH+DM+HFGWs: arXiv:2305.09194

Thank You!

Annihilation of Dark Matter After Evaporation of PBHS

- Issue may arise where annihilation of dark matter after PBH evaporation may lead to a lower relic abundance

$$\frac{\Gamma_{\chi\chi}(\tau_{PBH}+\epsilon)}{H(\tau_{PBH}+\epsilon)} \simeq \frac{n_\chi(\tau_{PBH}+\epsilon)\langle\sigma v\rangle_{\chi\chi}(\tau_{PBH}+\epsilon)}{H(\tau_{PBH}+\epsilon)}$$

$$\langle\sigma v\rangle_{\chi\chi}(\tau_{\rm PBH}+\epsilon) = \frac{\alpha_\Lambda^2}{\Lambda^2}$$

$$n_\chi(\tau_{\rm PBH}+\epsilon) \simeq N_\chi \beta \frac{\rho_{\rm rad}(t_\star)}{M_{\rm PBH}} \frac{T^3(\tau_{\rm PBH})}{T^3(t_\star)}$$

$$\frac{\Gamma_{\chi\chi}(\tau_{PBH}+\epsilon)}{H(\tau_{PBH}+\epsilon)} < \frac{27\sqrt{2}\zeta(3)}{8192\times 2^{1/4}\sqrt{5}\pi^{7/2}} \frac{\sqrt{g_\star}}{(7g_\chi+8g_\phi)^{1/4}} \frac{\alpha_\Lambda^2\beta}{C} \frac{M_{\rm Pl}}{M_{\rm PBH}} \ll 1$$

The Need for a Multicomponent Dark Sector

- Typical FOPT Scenario: One scalar ϕ is massless in the true vacuum and fermion gains its mass from the symmetry breaking of the scalar. Fermion is the dark matter candidate.

  $y_\chi \phi \bar{\chi}\chi$ $\bar{\chi}\chi \rightarrow \phi\phi$

- The annihilation of a fermion to a massless scalar leads to energy density leaving the pocket. This highly suppresses PBH formation and therefore inhibits recycling.

  Recycling: $\langle\phi\rangle \sim \mathcal{O}(55-60) \times T_* \times (1/y_\chi)$

Possible Questions/ Extra Information

How do ϕ and χ affect PBH formation?

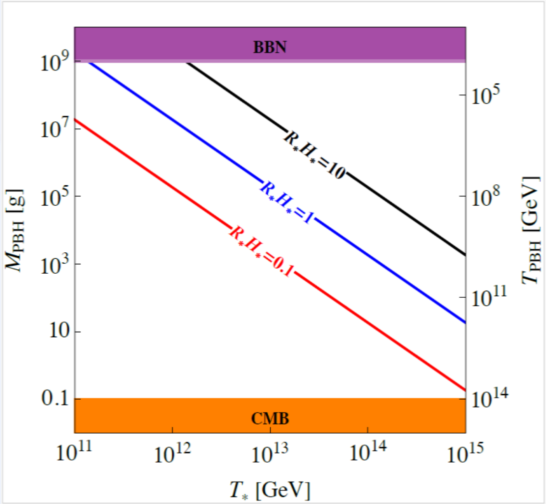
An attractive force caused by ϕ particles (Yukawa force) could enhance PBH formation by causing χ particles to collapse before the degeneracy pressure becomes important. However, we did not pressure the strength of this force in our work, but detailed calculation needs to be done.

$T > \Lambda$ $\quad \sigma_{\rm ann} = \alpha_\Lambda^2/T^2$ $\quad \Gamma_{\rm ann} = n_{\chi/\phi}\, \alpha_\Lambda^2/T^2 \propto T$

$T \lesssim \Lambda$ $\quad \Gamma_{\rm ann} = n_{\chi/\phi}\, \alpha_\Lambda^2/\Lambda^2 \propto T^3$

$T_\star \lesssim T \lesssim \Lambda$

$$\mathcal{L} \supset -y_\chi \phi \bar{\chi}\chi + \mu^2\phi^2 - \lambda\phi^4 + \mathcal{L}_{\rm SM-DS}$$



Fermi Ball Scenario: A fermion asymmetry in the pocket leads to Fermi ball formation while the scalar is massless leading to a recycling scenario

Black Hole Thermodynamics

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

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

$$\frac{dM_{\rm BH}}{dt} = -4\pi r_S^2 \sum_i \int_0^\infty \frac{d^2u_i(E,t)}{dtdE} dE = -\frac{g_*(T_{\rm BH})}{30720\pi}\frac{M_{\rm Pl}^4}{M_{\rm BH}^2}$$

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

$$\tau = \frac{10240\pi}{g_*(T_{\rm BH})}\frac{M_i^3}{M_{\rm Pl}^4}$$

D. Baumann, P. Steinhardt, and N. Turok 2007
arXiv:hep-th/0703250v1

P. Gondolo, P. Sandick, and B. Shams Es Haghi 2020

r_s ≡ Schwarzschild radius
T_{BH} ≡ Black Hole Temperature
M_i ≡ Initial Mass of Black Hole
Tau ≡ We take this to be the Evaporation time
t_i ≡ Formation time
u_i ≡ Energy density
M_{Pl} ≡ Reduced plank mass
M_{Pl} ≡ 1.220 890 x 10^{19} GeV