Recycling: A New Mechanism for Producing Ultra Heavy Particle Dark Matter

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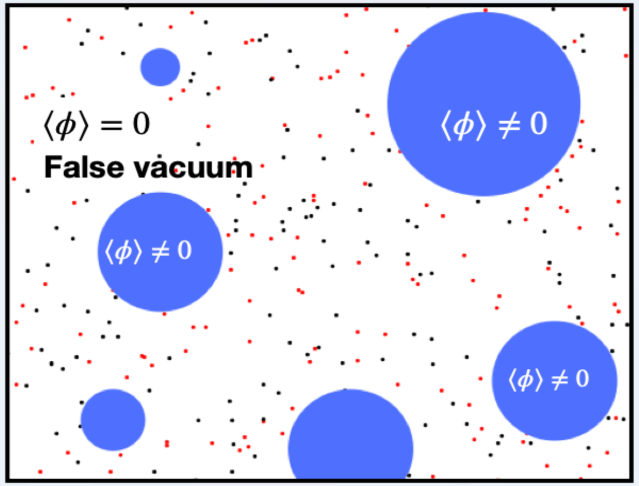
arXiv: 2310.08526

Outline of Talk

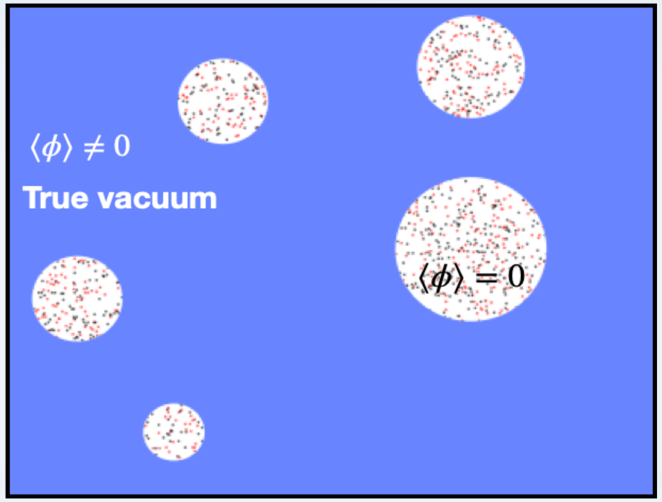
- Overall story of recycled dark matter
- Trapped (Multicomponent Dark Sector)
- PBH formation
- UHDM produced from PBHs

Recycling Mechanism

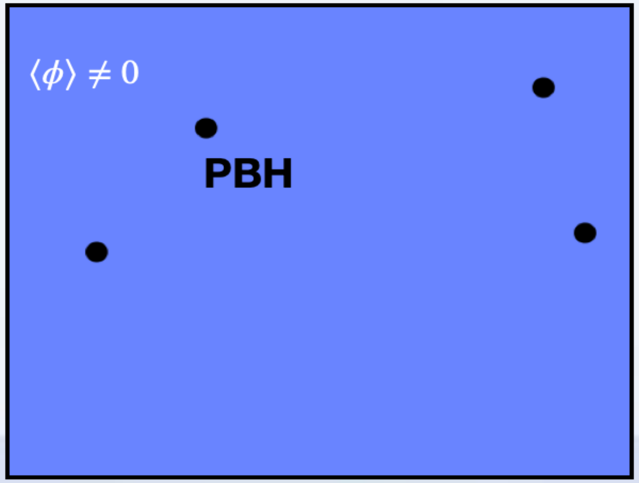
(1) First Order Phase Transition



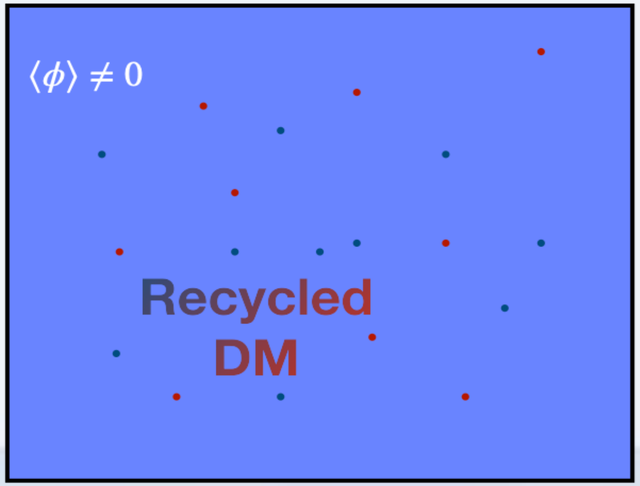
(2) Dark sector trapped



(3) Black hole formation



(4) Hawking radiation



Dark Sector FOPT

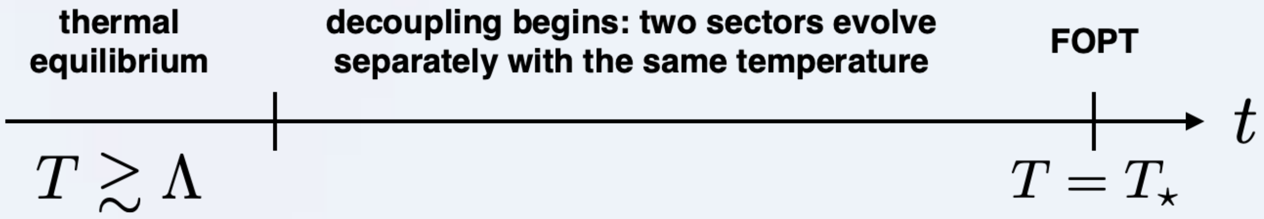
$$\mathscr{L} \supset -y_\chi \phi \bar{\chi}\chi + \mu^2\phi^2 - \lambda\phi^4 + \mathscr{L}_{\mathrm{SM-DS}}$$

heavy DM with Yukawa mass

responsible for FOPT

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

- $\mathscr{L}_{\mathrm{SM-DS}}$ can keep dark sector and SM sector in equilibrium before FOPT,



thermal equilibrium

decoupling begins: two sectors evolve separately with the same temperature

FOPT

t

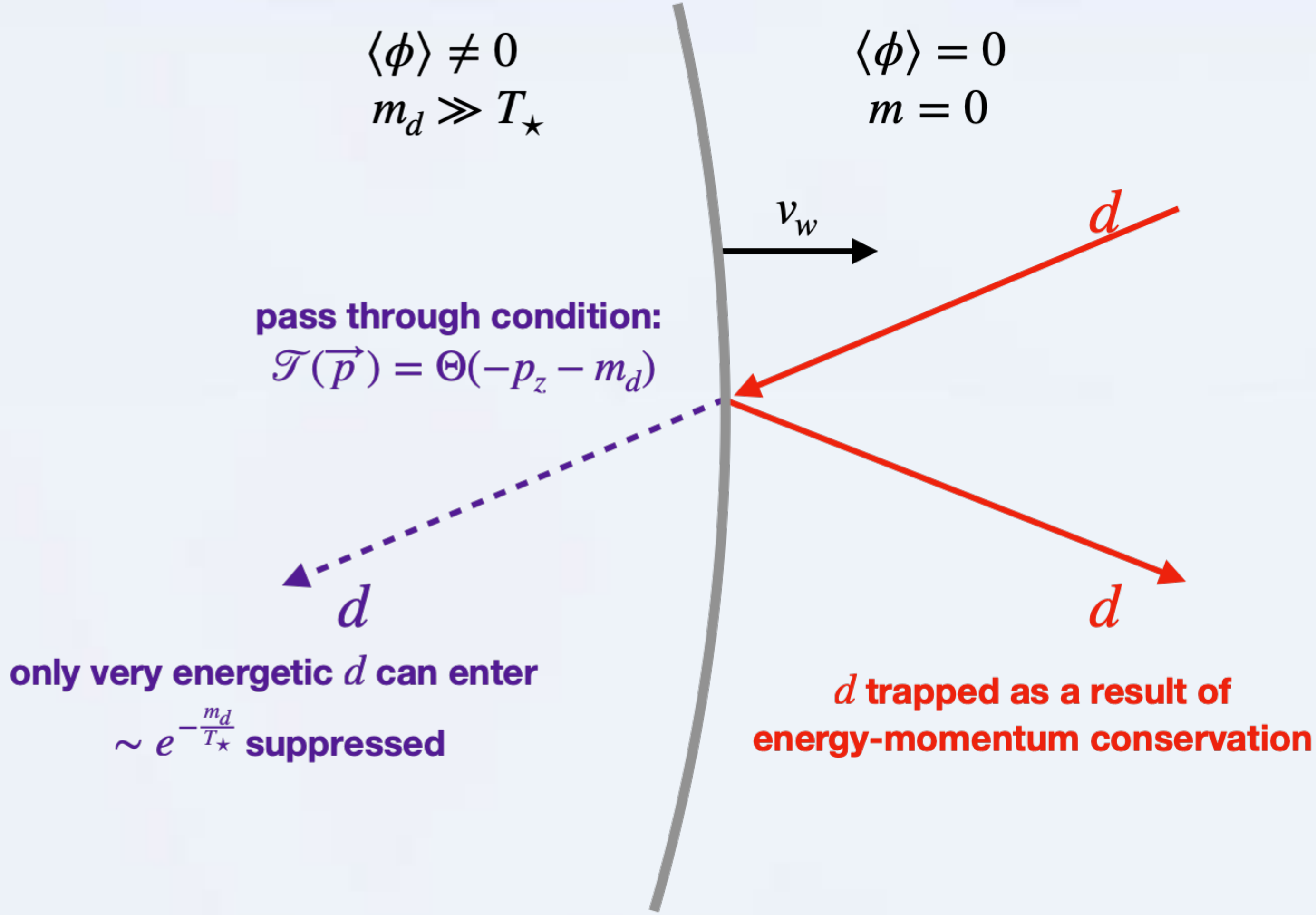
$T \gtrsim \Lambda$

$T = T_\star$

$$\alpha_\Lambda \gtrsim 0.17 \times \left(\frac{g_\star + g_\phi + \frac{7}{8}g_\chi}{106.75 + 4.5}\right)^{1/4} \left(\frac{\Lambda}{10^{16}\ \mathrm{GeV}}\right)^{1/2}$$

Lower bound to maintain kinetic equilibrium with SM

Trapped Dark Sector



pass through condition:
$\mathcal{T}(\overrightarrow{p}) = \Theta(-p_z - m_d)$

only very energetic d can enter
$\sim e^{-\frac{m_d}{T_\star}}$ suppressed

d trapped as a result of
energy-momentum conservation

M. Baker, J. Kopp, A. Long
1912.02830
M. Baker, M. Breitbach, J. Kopp, L. Mittnacht,
2105.07481, 2110.00005

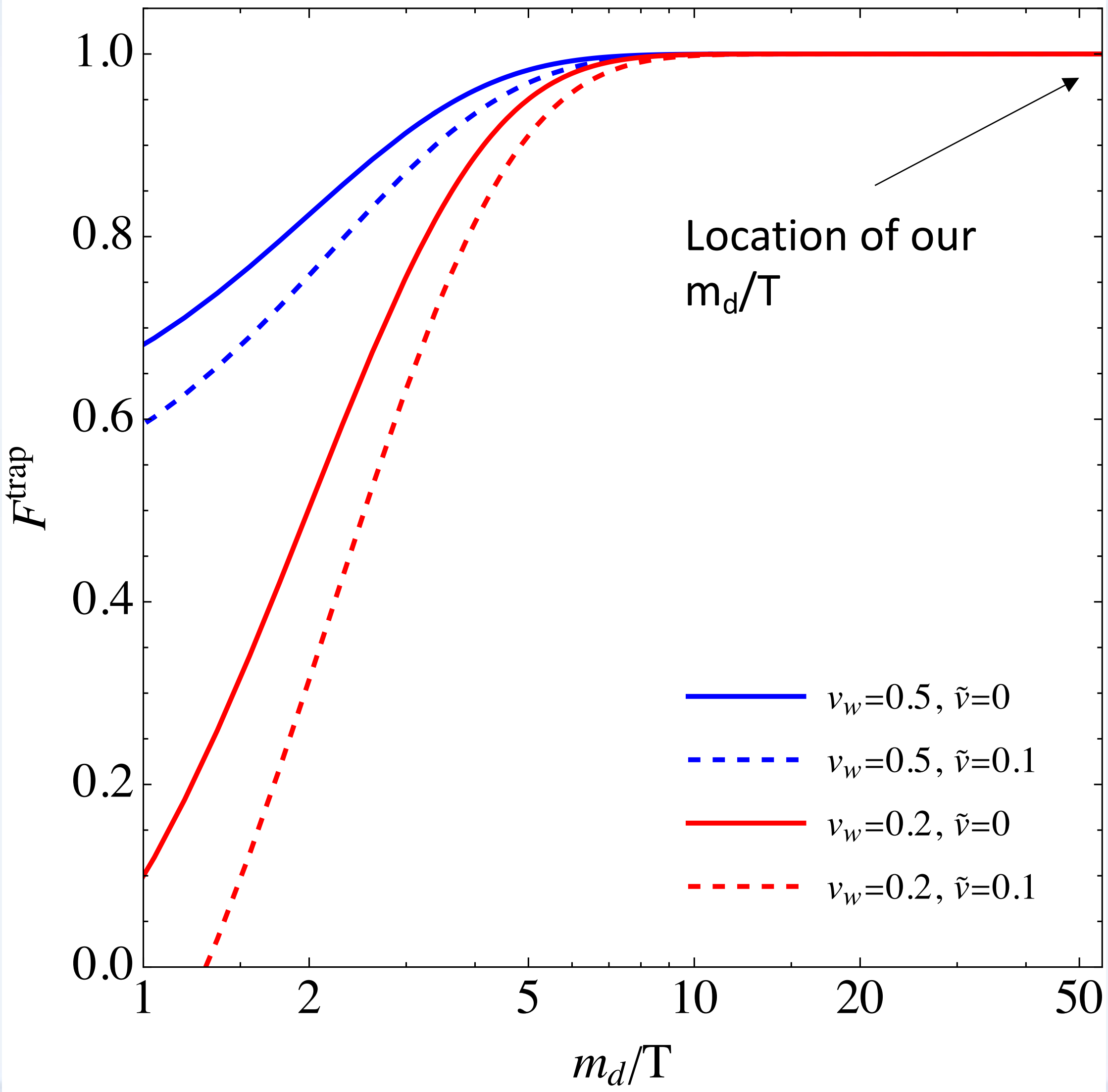
Trapped Dark Sector During FOPT

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

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

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

- 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



Location of our m_d/T

Thermal History

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

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

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

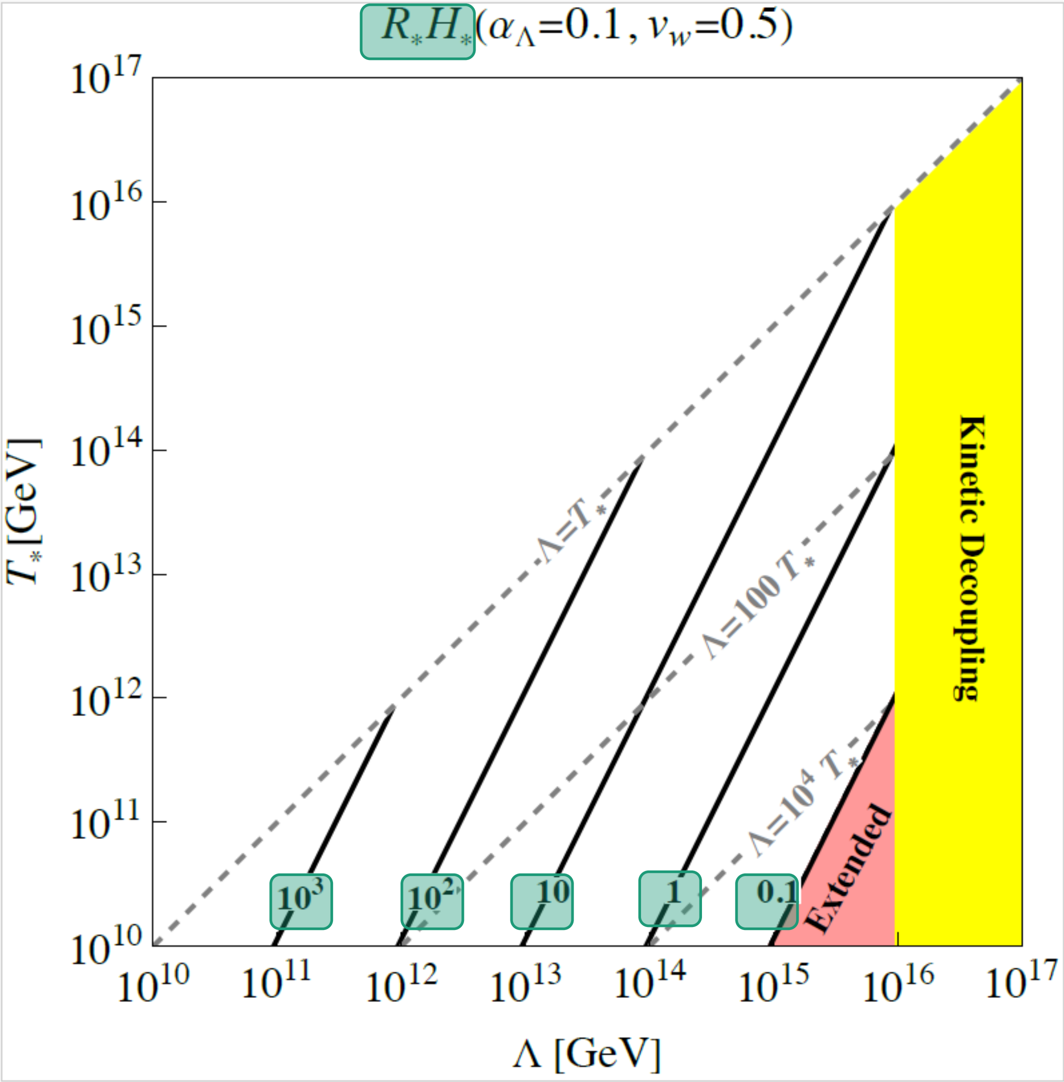
When T < Λ the cross section is a constant

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

Annihilation rate: $\Gamma_{\mathrm{ann}} = n_\chi \dfrac{\alpha_\Lambda^2}{\Lambda^2}$

Time scale of collapse: $t_c \simeq R_\star / v_w$

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



PBH Formation

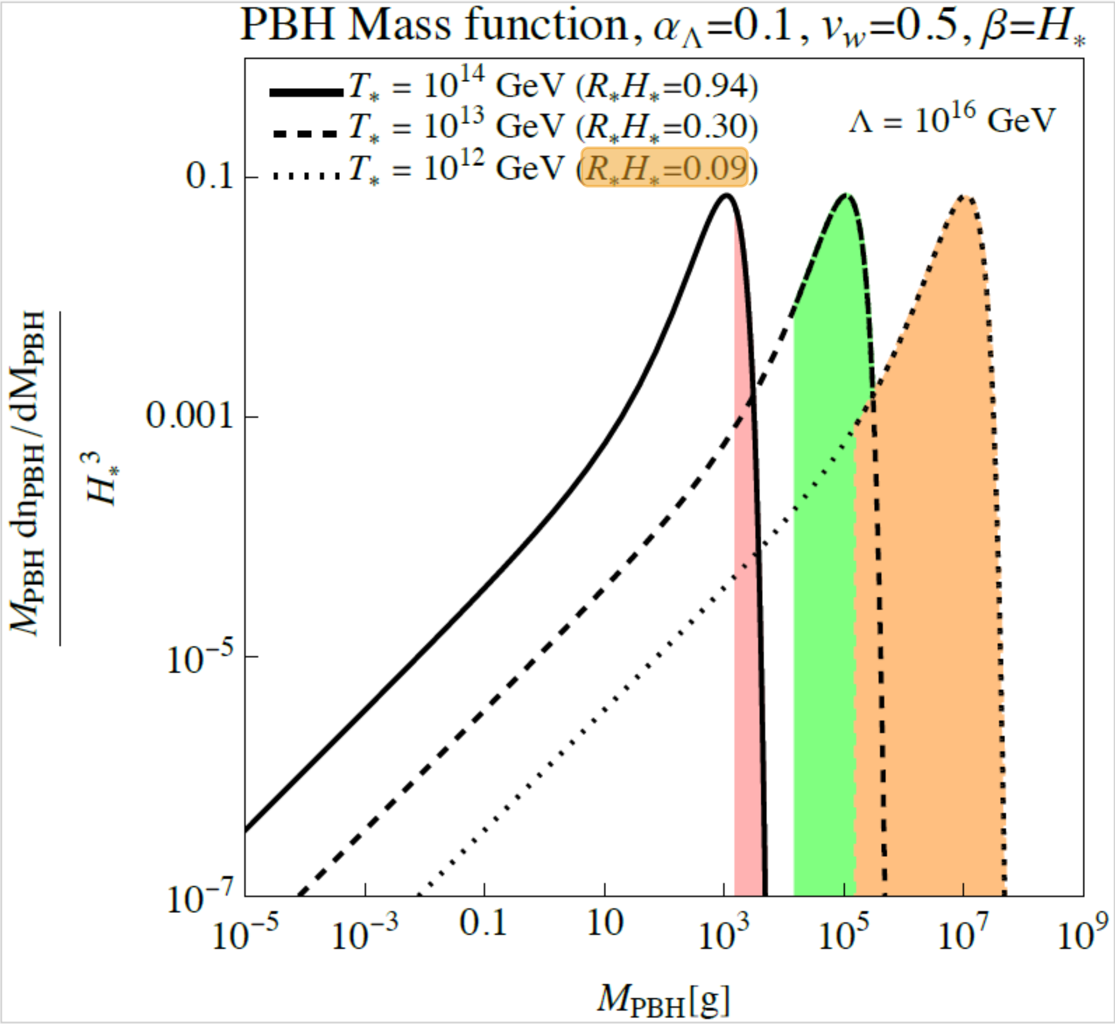
$$M_{\rm PBH} = \left[\frac{2\pi^3}{90}\left(g_\phi + \frac{7}{8}g_\chi\right)\right]^{1/2} R_\star^2 T_\star^2 M_{\rm Pl}$$

Include lower bound due to annihilation in small pockets

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

$$\frac{dn_{\rm PBH}}{dM_{\rm PBH}} \simeq \frac{I_\star^4\,\beta^4 M_{\rm PBH}^{-1/2}}{384\,T_\star\, v_w^3 \left(\frac{2\pi^3}{90G}\left(g_\phi + \frac{7}{8}g_\chi\right)\right)^{1/4}} \boxed{e^{4\beta R_\star/v_w - I_\star\, e^{\beta R_\star/v_w}}} \left(1 - e^{-I_\star e^{\beta R_\star/v_w}}\right)$$
$$\times\Theta\left(M_{\rm PBH} - \boxed{6.9\times 10^{-3}\sqrt{g_\phi + \frac{7}{8}g_\chi}\,\frac{\alpha_\Lambda^2}{v_w}\,\frac{M_{\rm Pl}^4}{T_\star\Lambda^2}}\right)$$

Lower cutoff of $M_{\rm PBH}$ due energy leaving the pocket



PBH Evaporation & DM Relic Abundance

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

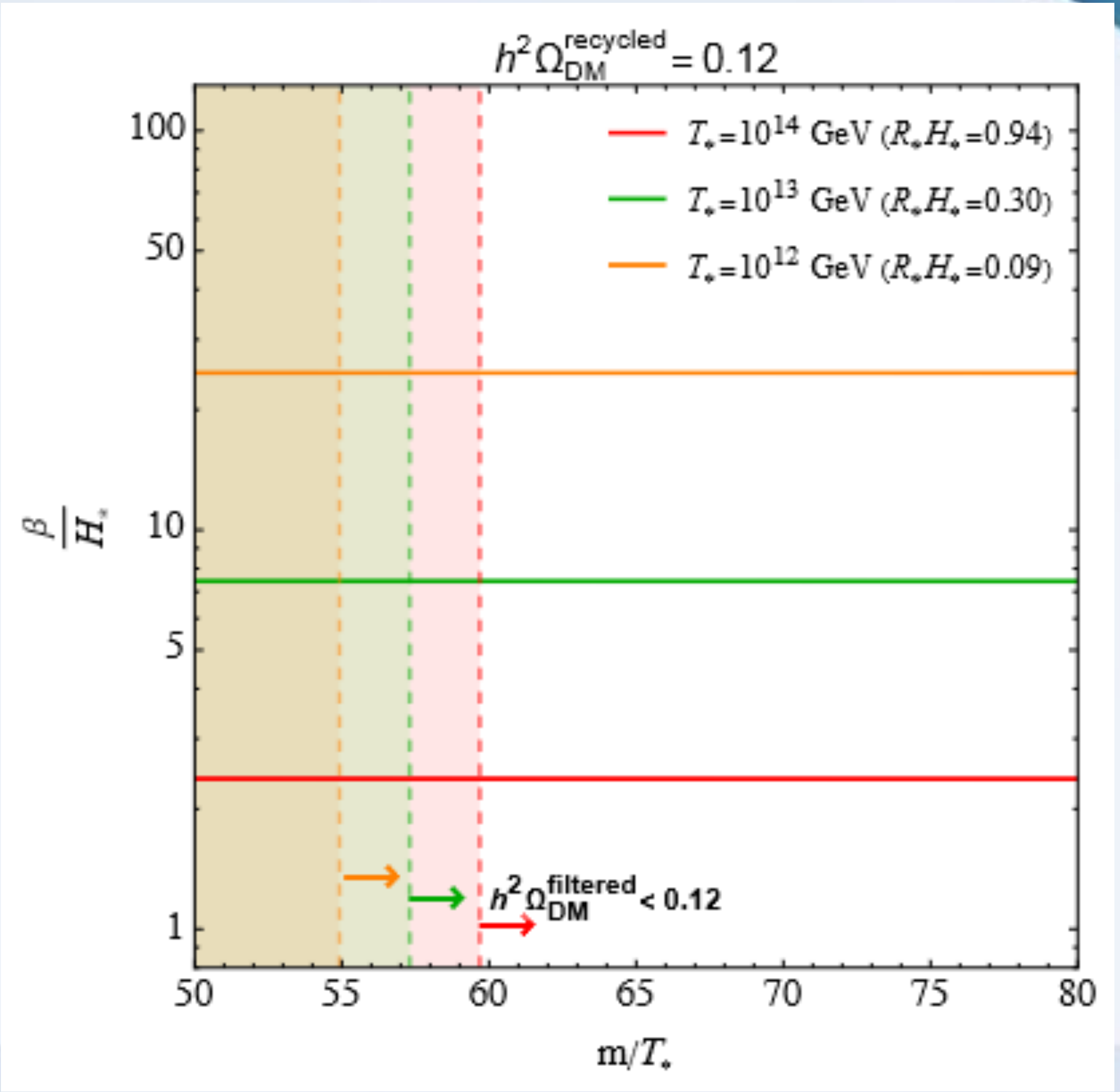
$$N_i = \frac{120\,\zeta(3)}{\pi^3}\frac{g_i}{g_\star(T_{\rm PBH})}\boxed{\frac{M_{\rm PBH}^2(t_\star)}{M_{\rm Pl}^2}}, \qquad T_{\rm PBH}(t_\star) > m_i,$$

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

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

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

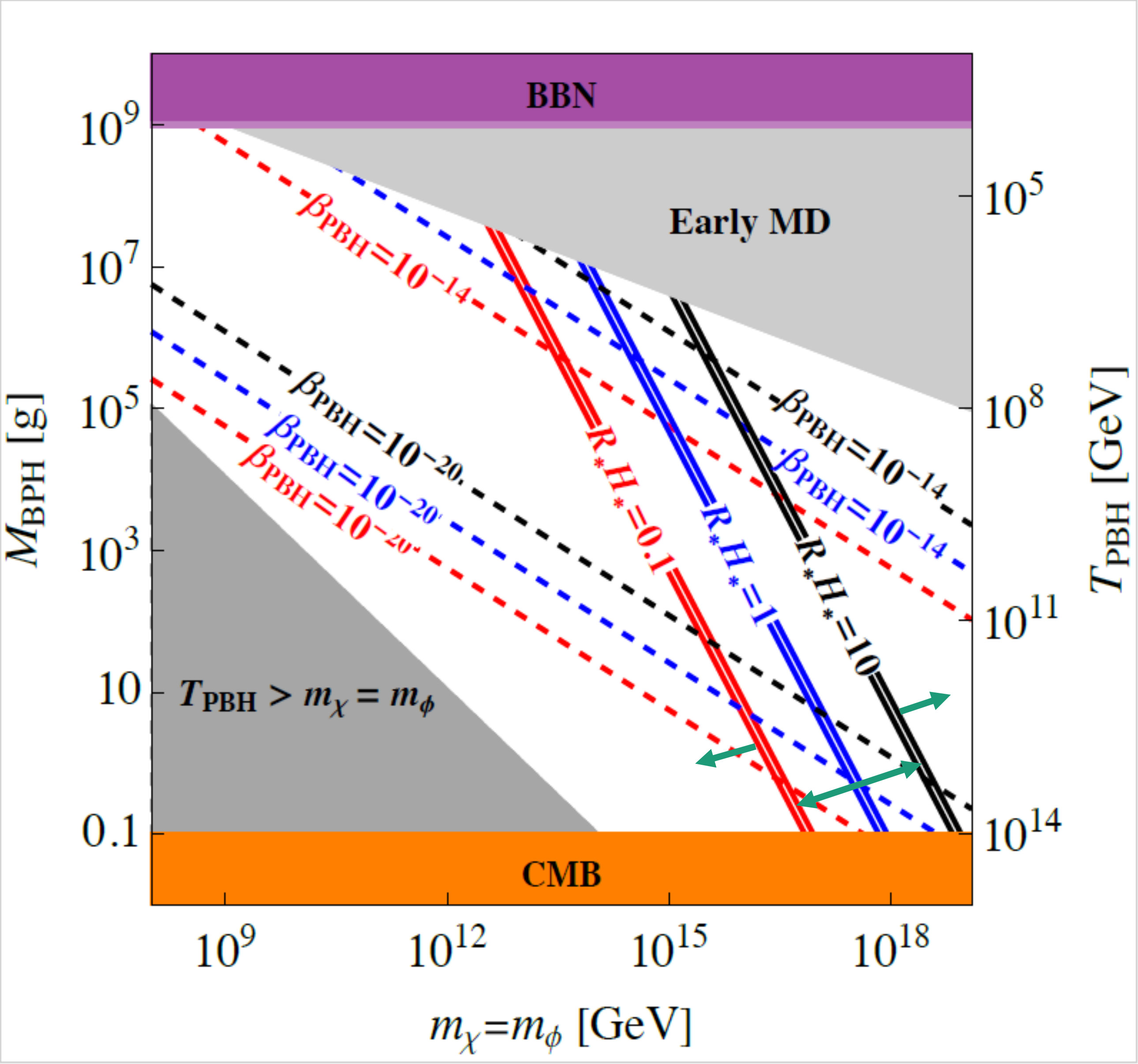
$$\Omega_{DM} = \frac{45\sqrt{3}\times 5^{1/4}\zeta(3)}{16\times 2^{1/4}\pi^{23/4}}\frac{(3g_\chi+4g_\phi)(7g_\chi+8g_\phi)^{1/4}}{(8g_\star+7g_\chi+8g_\phi)^{3/2}}\boxed{\beta_{\rm PBH}\frac{R_\star}{H_\star^{-1}}\frac{s(t_0)}{m\rho_c}\frac{M_{\rm Pl}^{7/2}}{M_{\rm PBH}^{3/2}}}$$



Recycling Dark Matter Parameter Space

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

- Left arrow: Everything left is excluded since this leads to an extended mass function which we leave for future study
- Right arrow: Everything right is excluded since our choice of cut off scale leads effective field theory breaking down in this area
- Double arrow: Everything in between is viable since filtering is exponentially suppressed.



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.
- New mechanism for generating Ultra Heavy Dark Matter
- 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

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

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

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

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

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.

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

- 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?

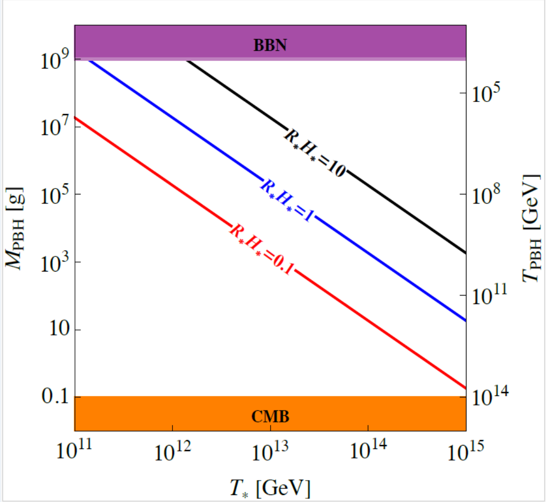
An attractive force caused by ϕ particles (Yukawa force) could enhance PBH formation by causing χ particles to collapse before the degeneracy pressure becomes important. However, we did not pressure the strength of this force in our work, but detailed calculation needs to be done.

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

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

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

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



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

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

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

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

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

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

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

$\chi\ \phi,\ m_{\chi/\phi} = 0$

$\chi\ \phi$ SM