Regurgitated Dark Matter: PBH Formation and Reemission

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Weakly Interacting Massive Particles

WIMP Miracle

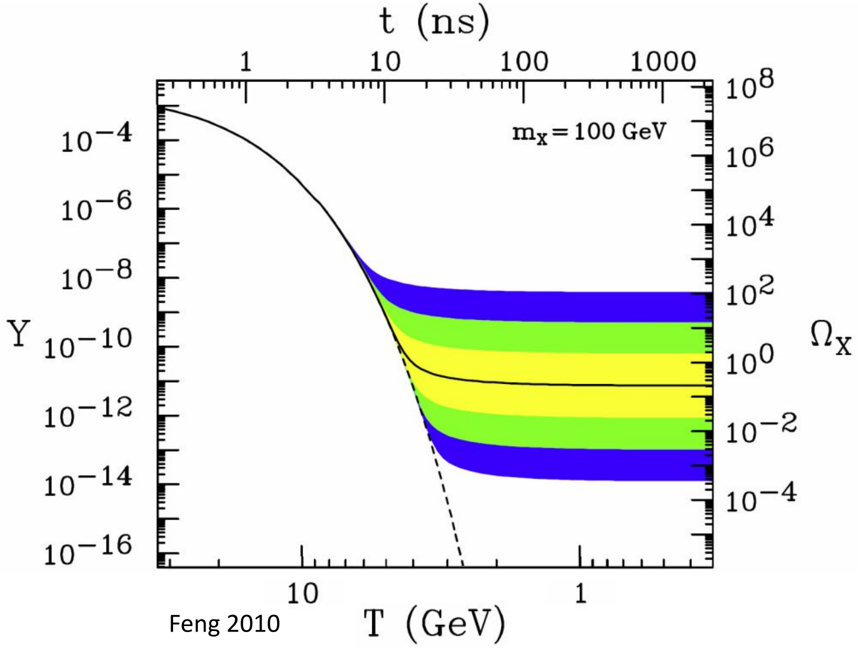
Can be produced by thermal freeze-out

Required cross-sections in the range of weak interactions

Lightest supersymmetric particle

Focus of large direct detection experiments

Not found



Feng 2010

Primordial Black Holes

Macroscopic dark matter candidate

Can comprise all of dark matter within the "mass window"

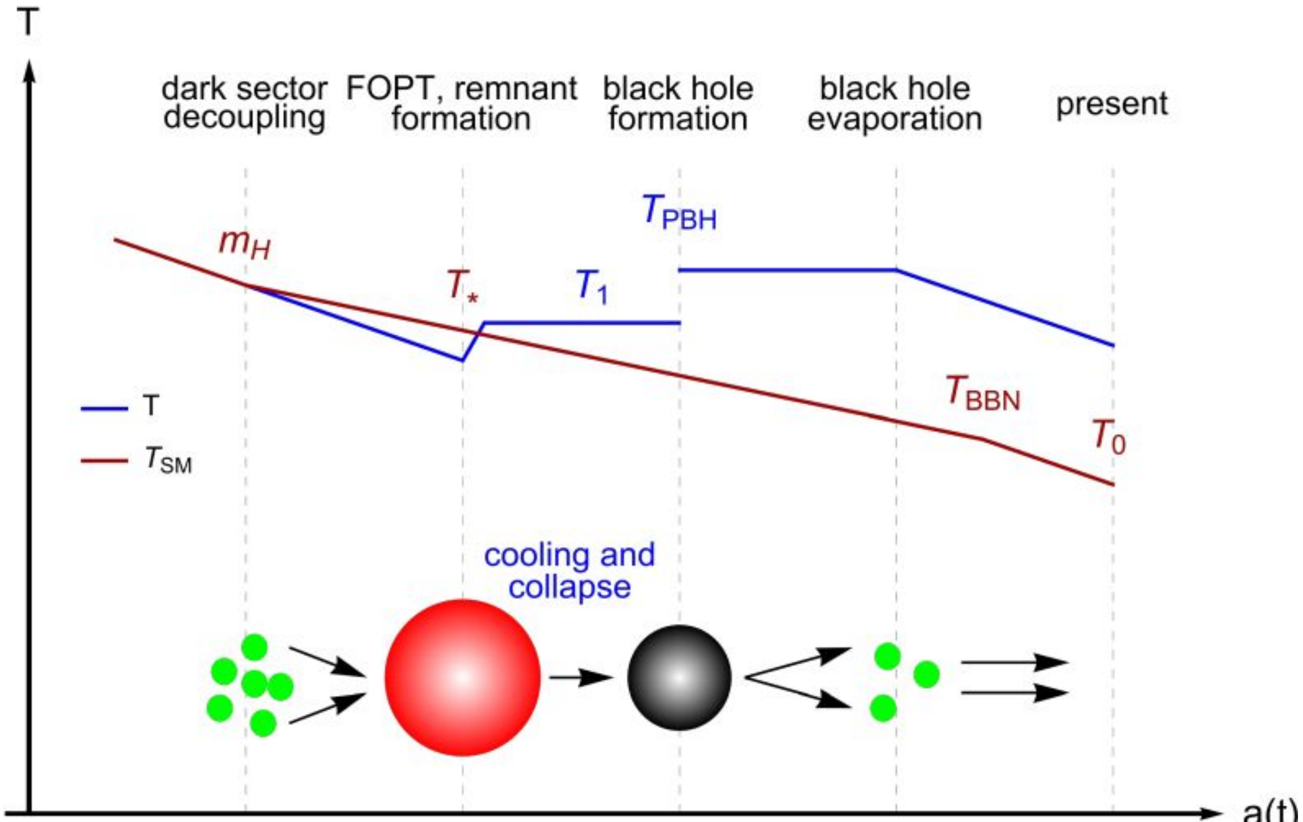
Natural consequence of inflation*

Produces Hawking Radiation

Formation scenarios usually result in gravitational waves

space.com

Timeline



T
dark sector decoupling
FOPT, remnant formation
black hole formation
black hole evaporation
present
T_{PBH}
m_H
T_*
T_1
T
T_{SM}
T_{BBN}
T_0
cooling and collapse
a(t)

Dark Sector Model

Simple model with (asymmetric) fermion and scalar

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{\mu^2}{2}\phi^2 - \frac{\kappa}{2}\phi^2(H^\dagger H) - V(\phi) + \bar{\chi}i\partial\!\!\!/\chi - y_\chi\phi\bar{\chi}\chi$$

Particle trapping:

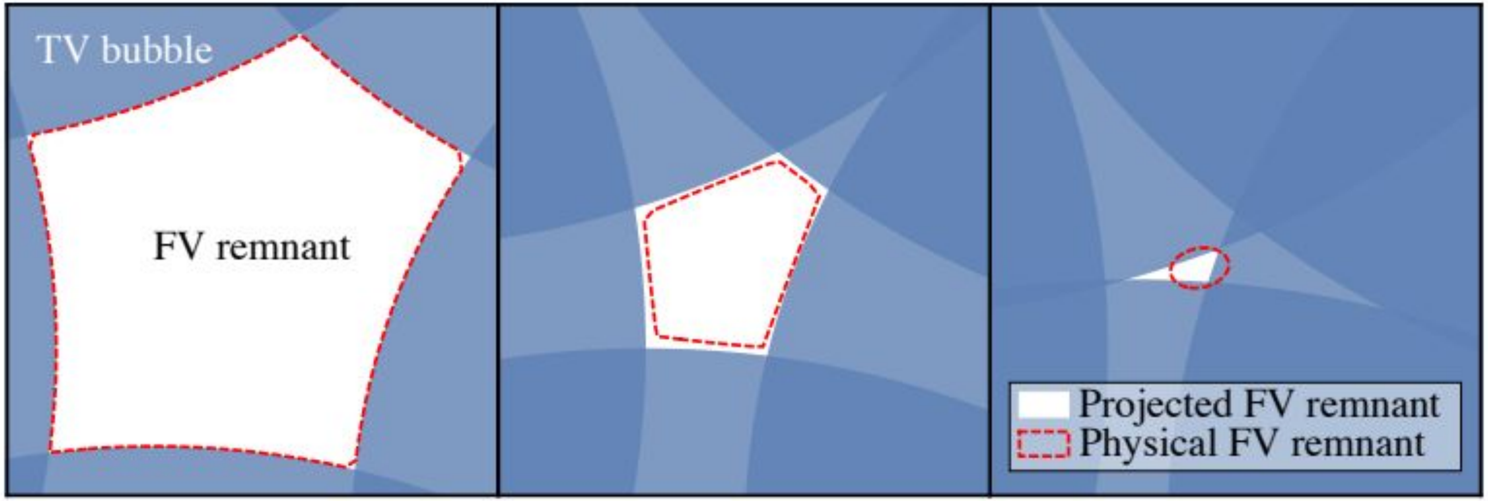
$$M_\chi^* \equiv y_\chi v_* \gg T_*, \quad M_\phi^* \equiv \left(\frac{\partial^2 V_{\rm eff}(\phi, T_*)}{\partial\phi^2}\right)^{1/2}\Bigg|_{\phi=v_*} \gg T_*$$

Fermion asymmetry leads to PBH

Initial Collapse

True bubble walls expand

Trapped particles confined to compact remenants



Pressure Balance

Inward Vacuum Pressure vs. Outward Thermal Pressure

$$T_1 = \left(\frac{90 \Delta V_{\rm eff}}{\pi^2 g_D} \right)^{1/4}$$

Homeostasis: Cooling->Shrinking->Latent Heat

Transition to Fermi ball supported by Fermi pressure:

$$R_{\rm tr} \sim \eta_\chi^{1/3} R_1$$

SM Portal Cooling

Trapped φ particles -> annihilations through Higgs coupling

$$\dot{C} = n^2 \langle 2E \rangle \sigma v_{\rm rel} = \frac{0.051 \kappa^2 T_1^7 m_f^2}{m_H^4}$$

Suppressed by Higgs mass, more efficient than evaporation

$$T_{\rm SM}^{\rm tr} \simeq 10^4 \text{ GeV} \, \kappa \left(\frac{T_1}{1 \text{ GeV}} \right)^{3/2}$$

Can saturate to blackbody radiation, different channels at high temperature

PBH Formation

Yukawa force becomes long range

$$L_\phi(T_D) = m_\phi(T_D)^{-1} = \frac{1}{\sqrt{\mu^2 + cT_D^2}}$$

Rapid collapse to PBH

Average mass:

$$\overline{M}_{\mathrm{PBH}} \sim 7 \times 10^6 \; g \; \left(\frac{\beta/H}{10^4}\right)^{-3} \left(\frac{\eta_\chi}{10^{-15}}\right) \left(\frac{T_*}{1 \text{ GeV}}\right)^{-2}$$

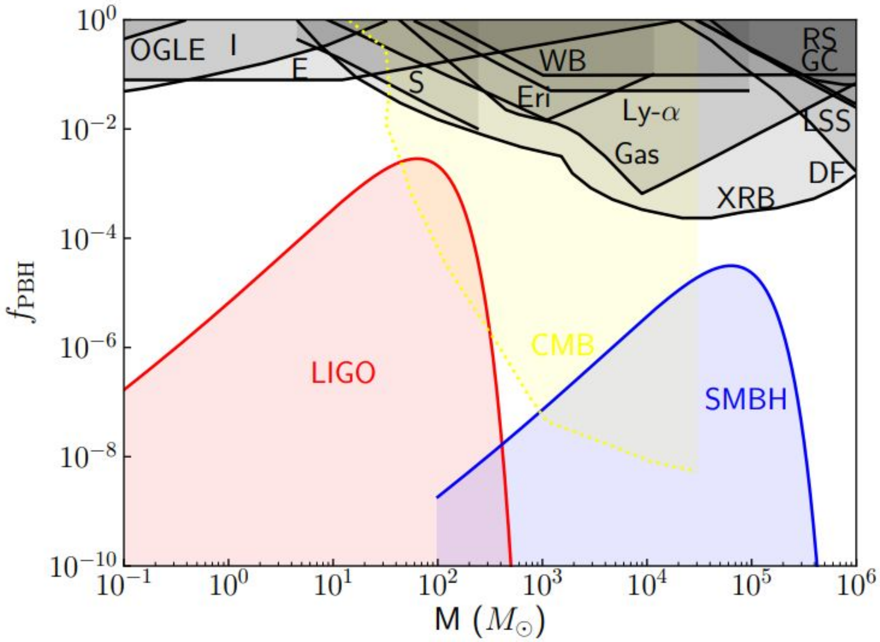
Fermi Ball PBH

Robust mechanism for PBH formation

Extreme slow cooling, long lived thermal ball dark matter

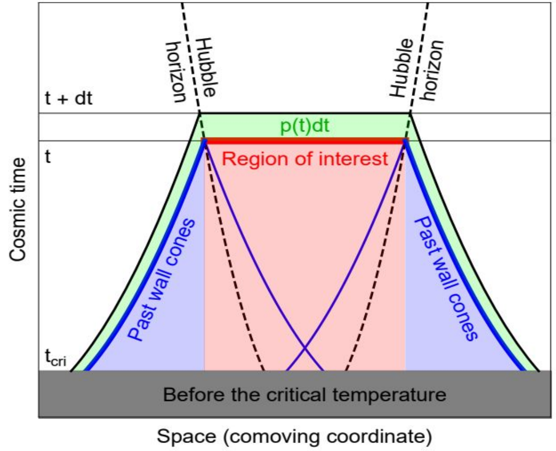
Evaporation cooling can form PBH late

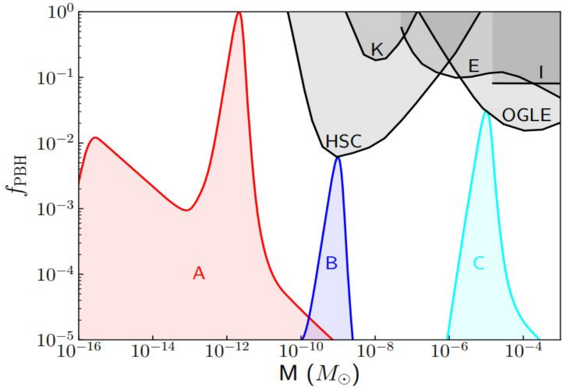
- Evade CMB bounds
- LIGO binary progenitors
- SMBH seeds



Other PBH Formation Mechanisms from FOPT

PBH formation facilitated by first-order QCD transition
Masses varies relative to standard QCD transition





Vacuum energy could seed overdensities

Long-lived false vacuum regions could cross critical formation thresholds

Evaporating PBH

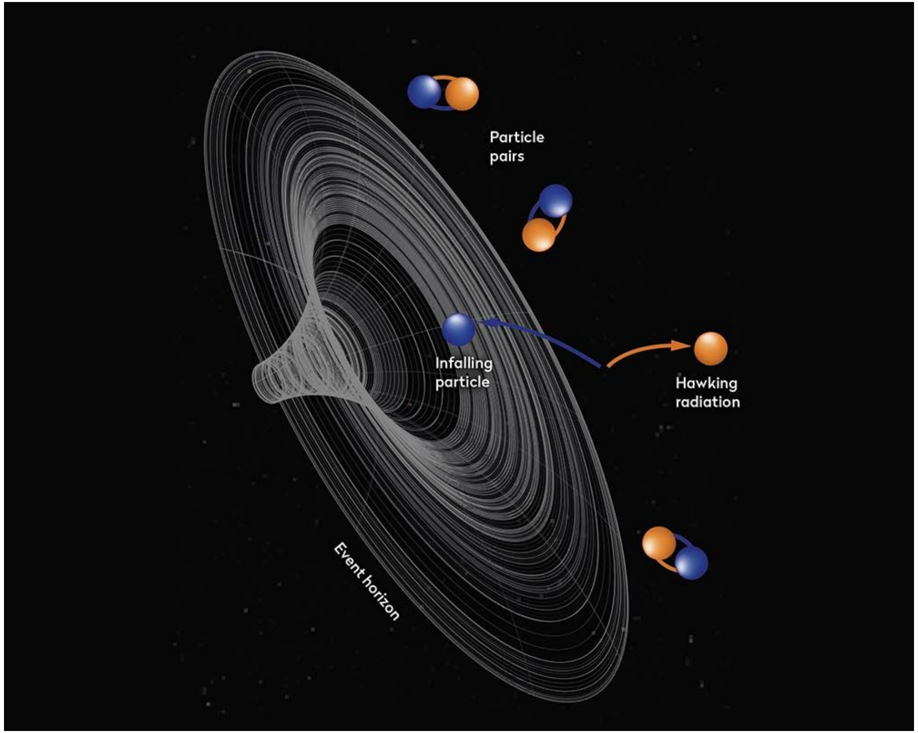
Recent interest on very light PBH

Hawking Temperature

$$T_{\mathrm{PBH}} = 1.06 \times 10^5 \ \mathrm{GeV} \left(\frac{M_{\mathrm{PBH}}}{10^8 \mathrm{g}}\right)^{-1}$$

Hawking evaporation emits particles based on mass-> DM emission

What if DM produced PBH that produced DM?



Getty Images

Dark Matter Density

Initial abundance: $$\frac{\rho_{\phi,\chi}}{\rho_{\rm SM}} = \frac{g_{H,(\phi,\chi)}}{g_{\rm H,SM}}$$

Non-relativistic emission:

Particles heavier than Hawking temperature

Suppressed by particle emission threshold

$$\frac{M_{\rm PBH}^{\rm em}}{M_{\rm PBH}} = \epsilon_{\rm em} \left(\frac{M_{\rm PBH}}{10^8 g}\right)^{-1} \left(\frac{m_{(\phi,\chi)}}{10^5 \text{ GeV}}\right)^{-1}$$

Relativistic emission:

Particles lighter than Hawking temperature

Suppressed by redshift after emission

$$\gamma \sim \frac{m_(\phi,\chi)}{\epsilon T_{\rm PBH}}$$

Constraints

BBN constraints on FOPT/cooling/evaporation timescale

Decay of WIMPs $\Gamma_{\phi \to HH} \propto \frac{\kappa^2 \langle \phi \rangle^2}{m_\phi}$

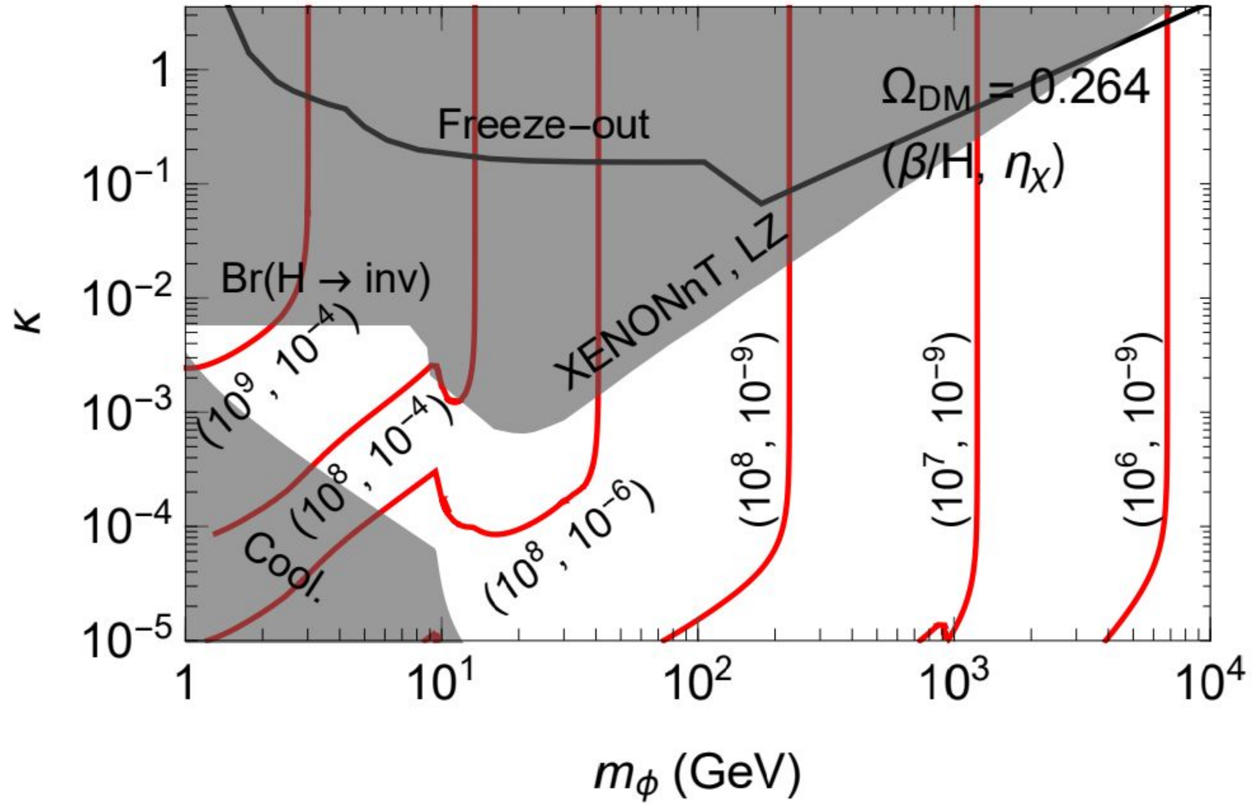
Direct detection experiments (XenonNT, LZ)

Invisible Decays (LHC)

Lyman-α bounds on warm dark matter

- Could apply to slightly less massive particles

WIMP Regurgitation



Conclusions

1. First order phase transition can trap WIMPs and form compact remnants, which eventually collapse into PBH.

2. Regurgitated dark matter is a novel production mechanism in which dark matter particles form PBH which reemit dark matter particles.

3. Due to the disassociation of interaction strength and abundance, WIMP parameter space is increased.