Regurgitated Dark Matter: PBH Formation and Reemission

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WIMPs and Primordial Black Holes: Introduction

Weakly Interacting Massive Particles

WIMP Miracle

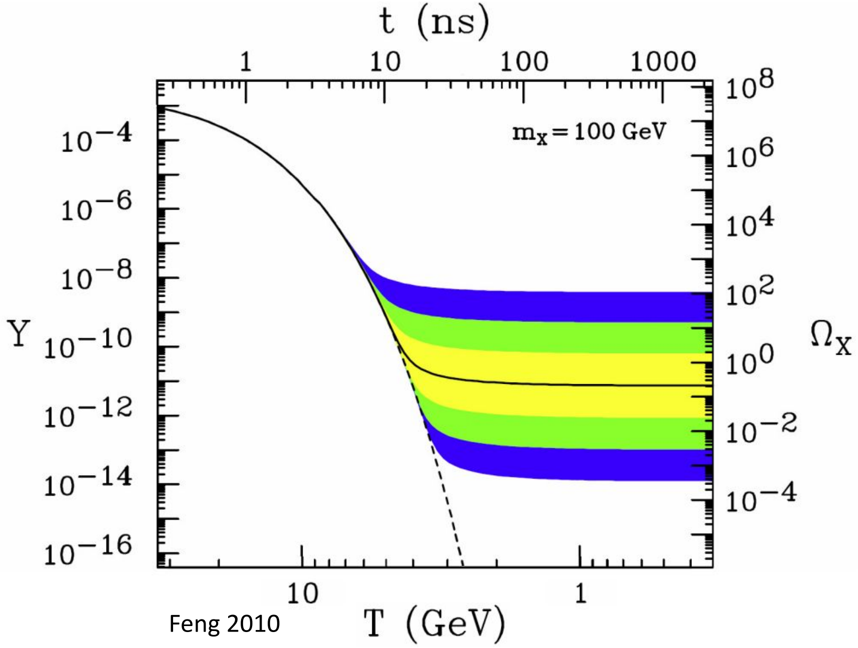
Can be produced by thermal freeze-out

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*

Formation scenarios usually result in gravitational waves

Produces Hawking Radiation

space.com

Primordial Black Holes: Hints

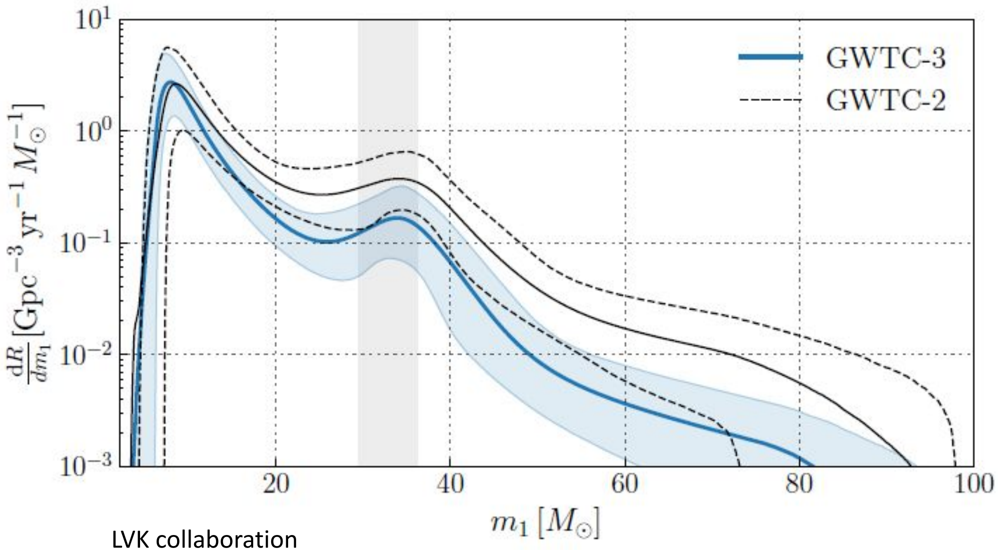
Can seed supermassive black holes
- Active Galactic Nuclei out to z=7
- JWST possible detection of z~10.6

Binary Black Hole Sources
- More black holes within "mass gap"
- Primordial origin vs. merger history

Possible relation to NanoGRAV signal

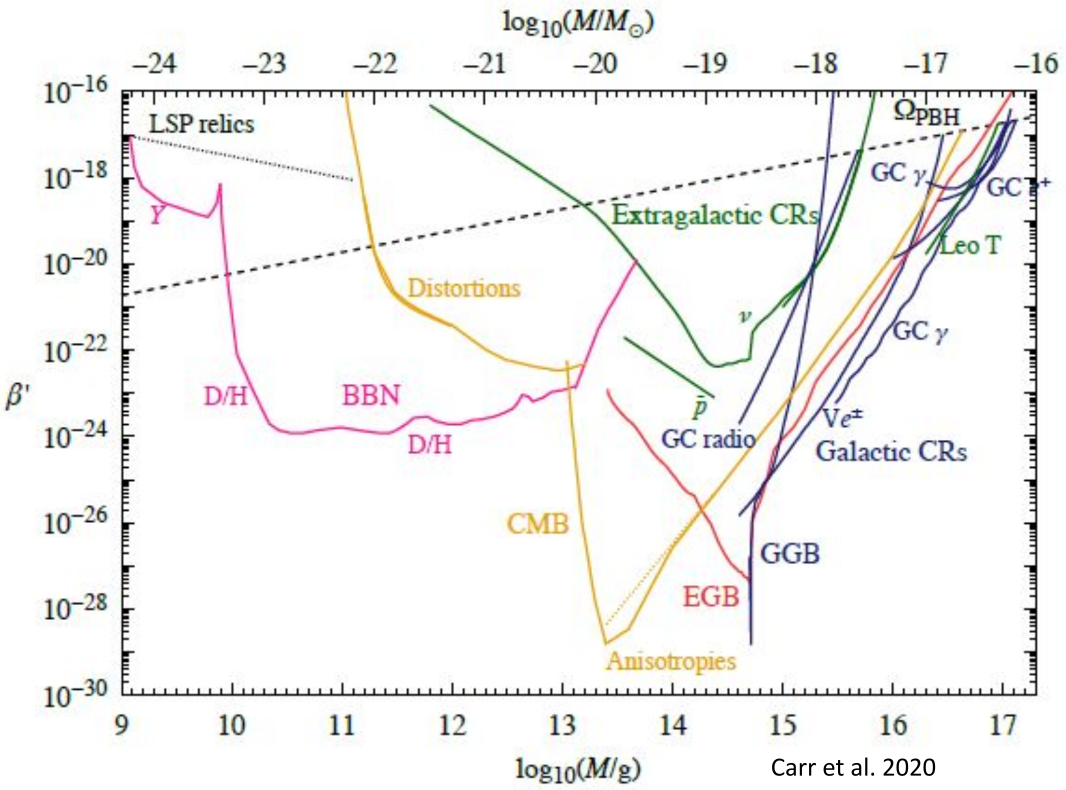
Microlensing candidate events

Emit Hawking Radiation



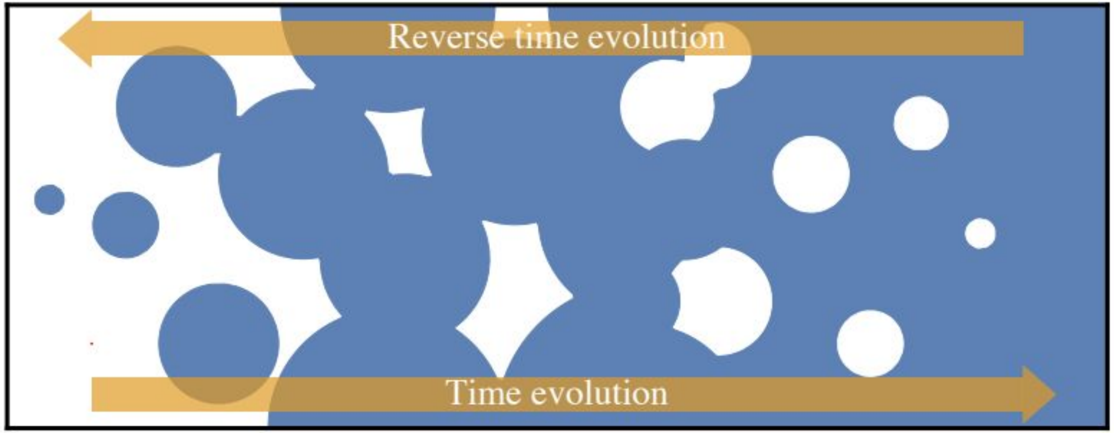
LVK collaboration

Light PBH Bounds

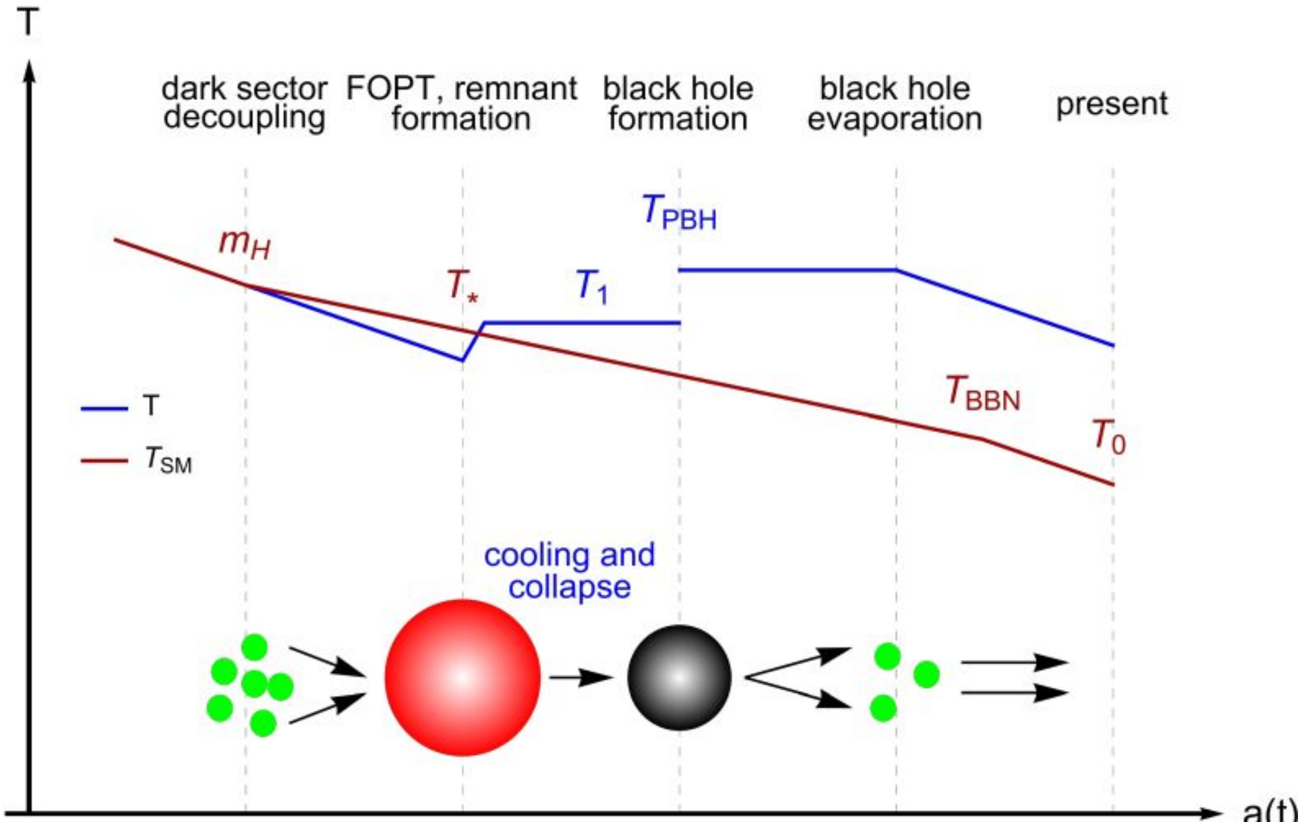


Carr et al. 2020

Primordial Black Holes from Dark Particles



Timeline


T
dark sector decoupling
FOPT, remnant formation
black hole formation
black hole evaporation
present
T_{PBH}
m_H
T_*
T_1
T_{BBN}
T_0
T
T_{SM}
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:

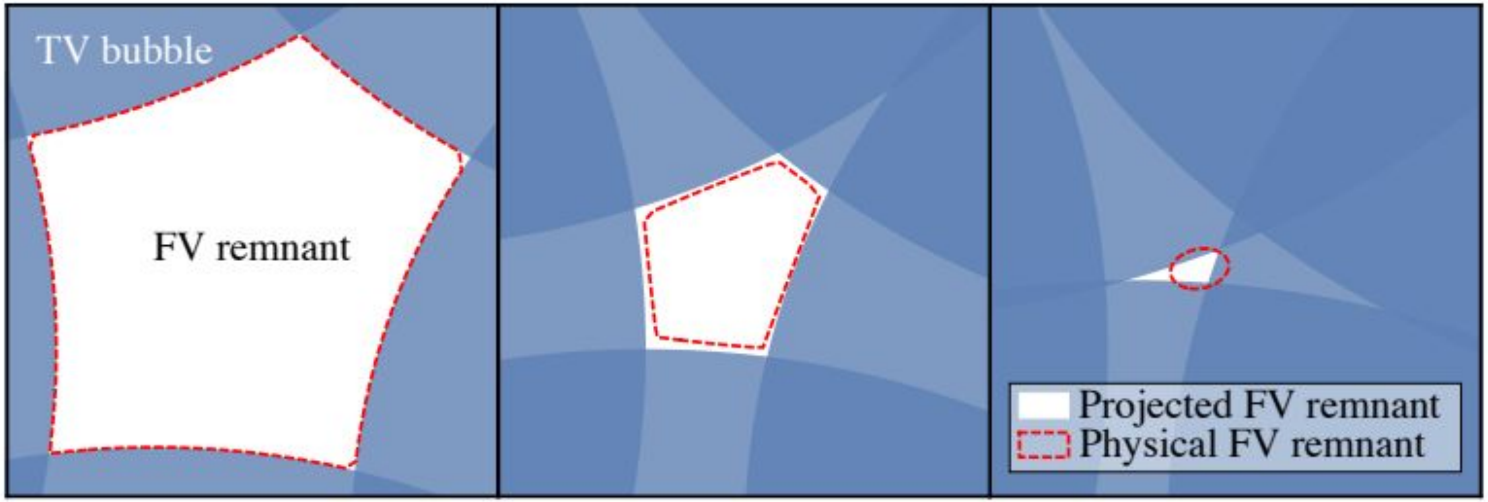
$$M_\chi^* \equiv y_\chi v_* \gg T_*, \quad M_\phi^* \equiv \left(\frac{\partial^2 V_{\rm eff}(\phi, T_*)}{\partial\phi^2}\right)^{1/2}\Bigg|_{\phi=v_*} \gg T_*$$

Fermion asymmetry leads to PBH

Initial Collapse

True bubble walls expand

Trapped particles confined to compact remnants



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

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

Can saturate to blackbody radiation, different channels at high temperature

PBH Formation

Yukawa force becomes long range: $y_\chi \phi \bar{\chi} \chi$

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

Rapid collapse to PBH

Average mass:

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

Remnant Endpoints

Thermal Balls

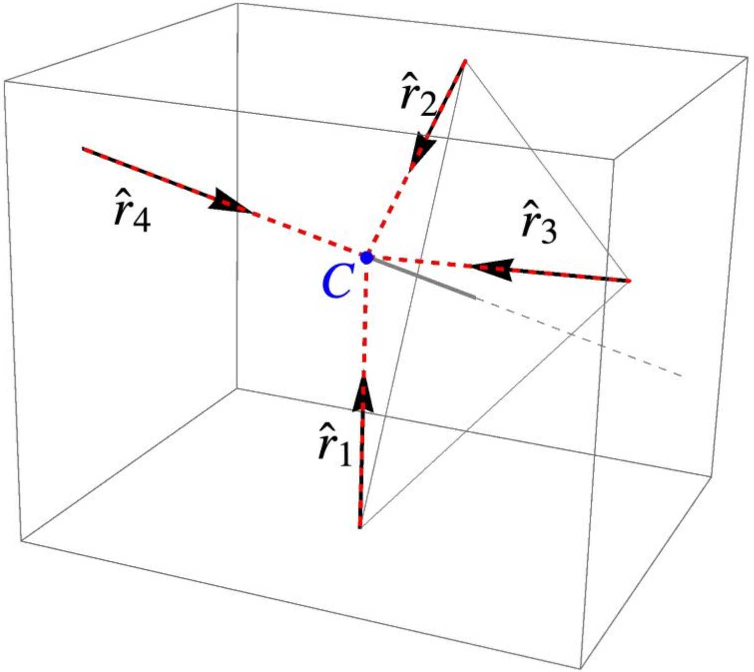
- Kept at constant temperature
- Semi-stable DM

Fermi Balls

- Mass from fermion asymmetry
- Unstable with strong Yukawa force

Primordial Black Holes

- Can efficiently form accretion disks
- Hawking radiation



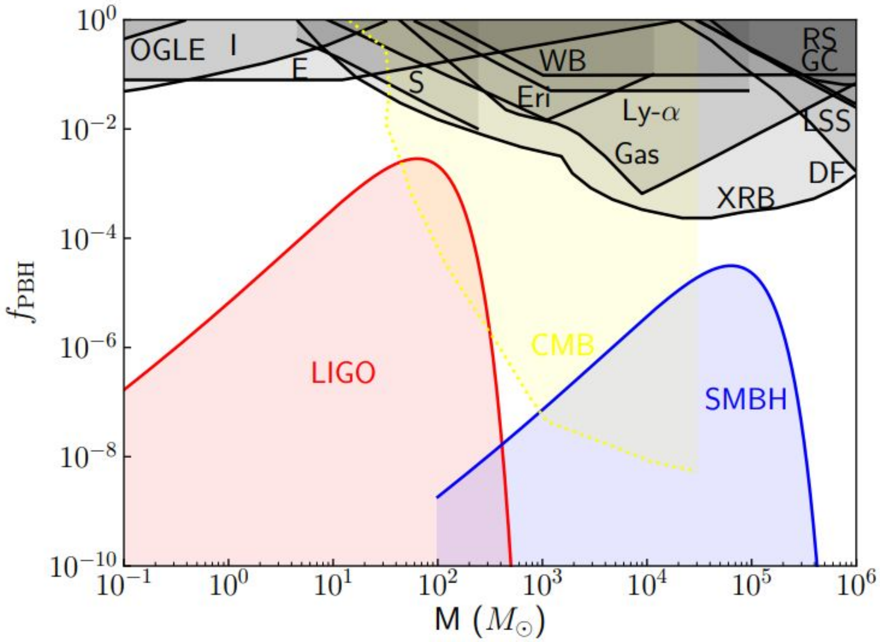
Late-Forming PBH

Robust mechanism for PBH formation

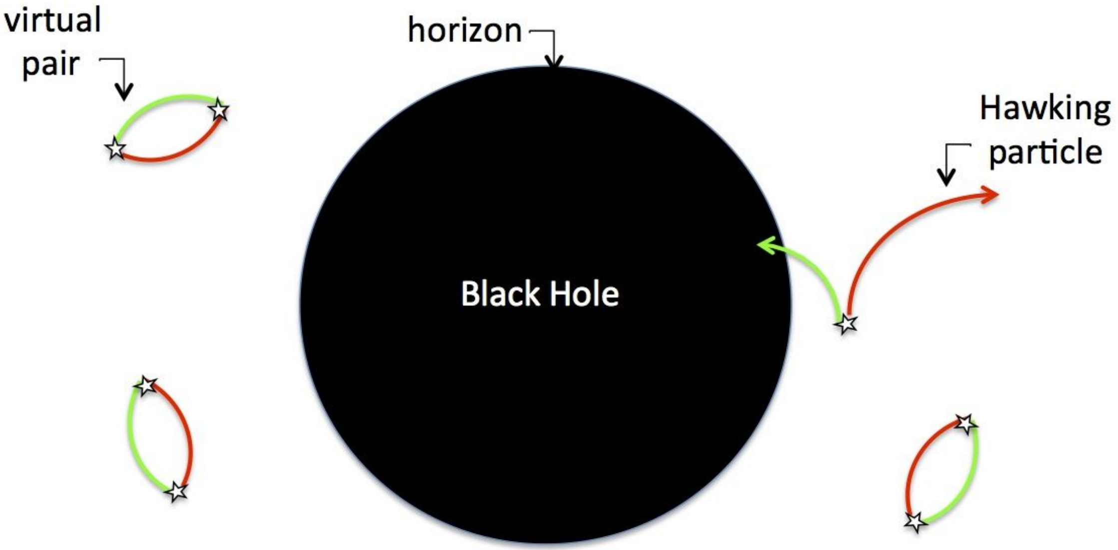
Extreme slow cooling, long lived thermal ball dark matter

Evaporation cooling can form PBH late

- Evade CMB bounds
- LIGO binary progenitors
- SMBH seeds



Dark Particles from Primordial Black Holes



Eurekasparks.org

Evaporating PBH

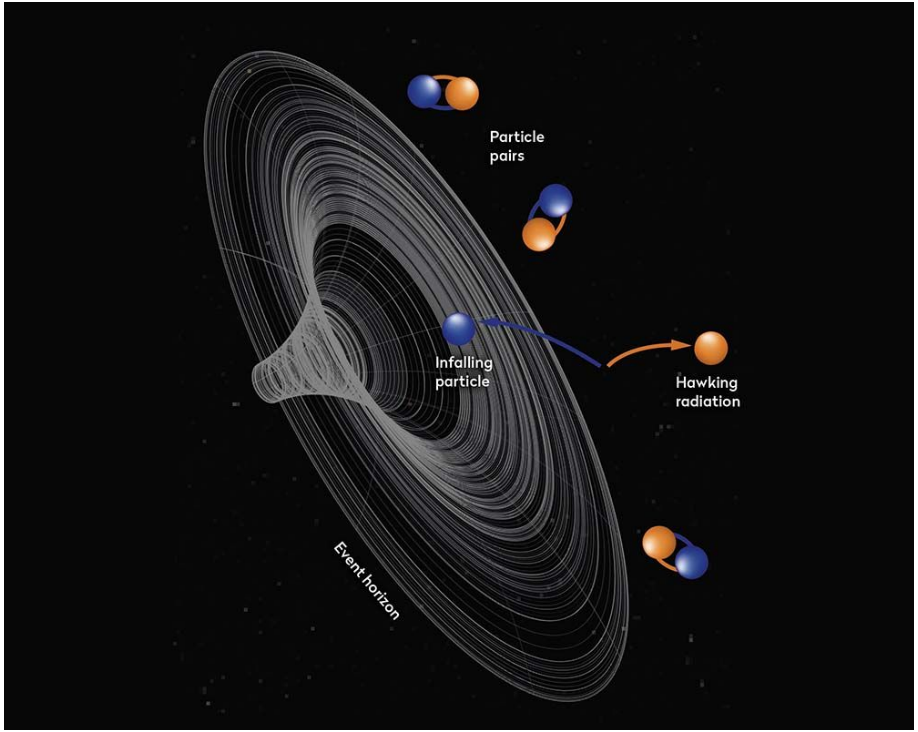
Recent interest on very light PBH

Hawking Temperature

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

Hawking evaporation emits particles based on mass-> DM emission

What if DM produced PBH that produced DM?



Getty Images

PBH Domination

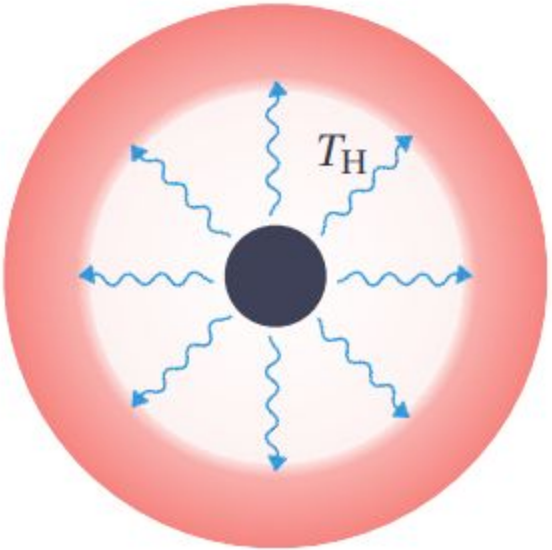
PBH density grows relative to plasma density

PBH domination before evaporation if

$$\beta \gtrsim 10^{-13} \left(\frac{M_{\rm PBH}}{10^8 g} \right)^{-1}$$

Reheating temperature

$$T_{\rm RH} = 50.5 {\rm MeV} \left(\frac{10^8 {\rm g}}{M_{\rm PBH}} \right)^{3/2}$$



He et al. 2022

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

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

Relativistic emission:

Particles lighter than Hawking temperature

Suppressed by redshift after emission

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

Constraints

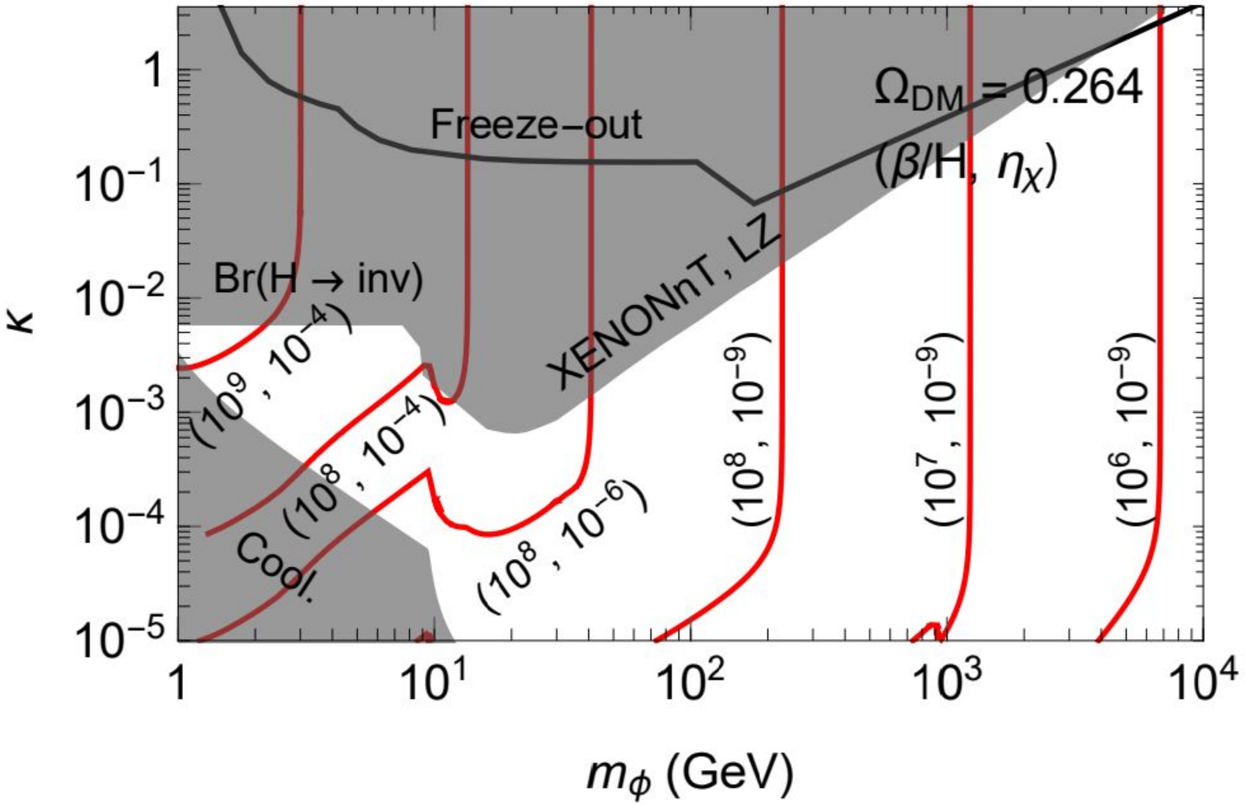
BBN constraints on FOPT/cooling/evaporation timescale

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)

WIMP Regurgitation



Conclusions

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

2. This PBH formation process can form PBH in the mass window, late-forming intermediate mass black holes, and evaporating PBH.

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

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