Regurgitated Dark Matter: PBH Formation and Reemission

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WIMPs and Primordial Black Holes: Introduction

Weakly Interacting Massive Particles

WIMP Miracle

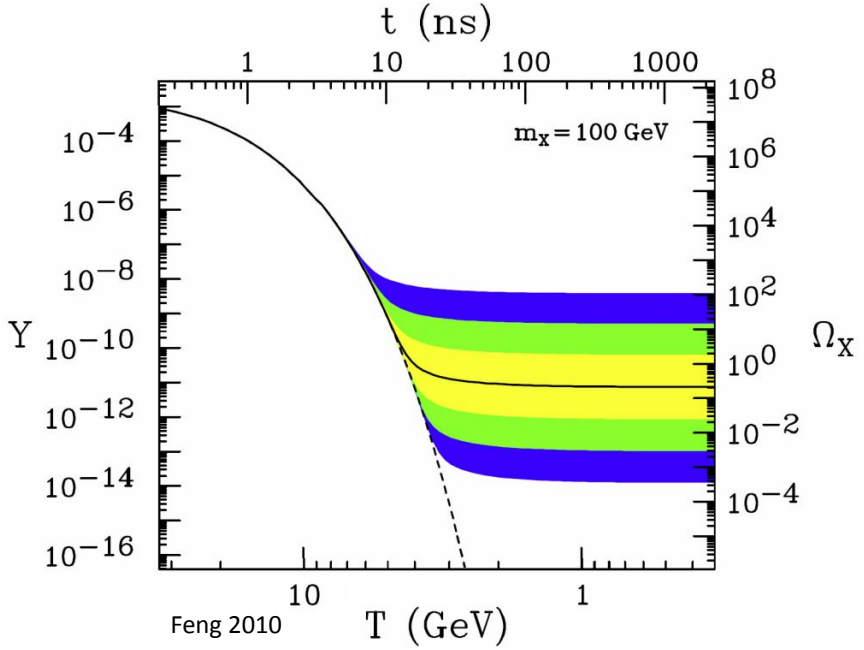
Can be produced by thermal freeze-out

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”

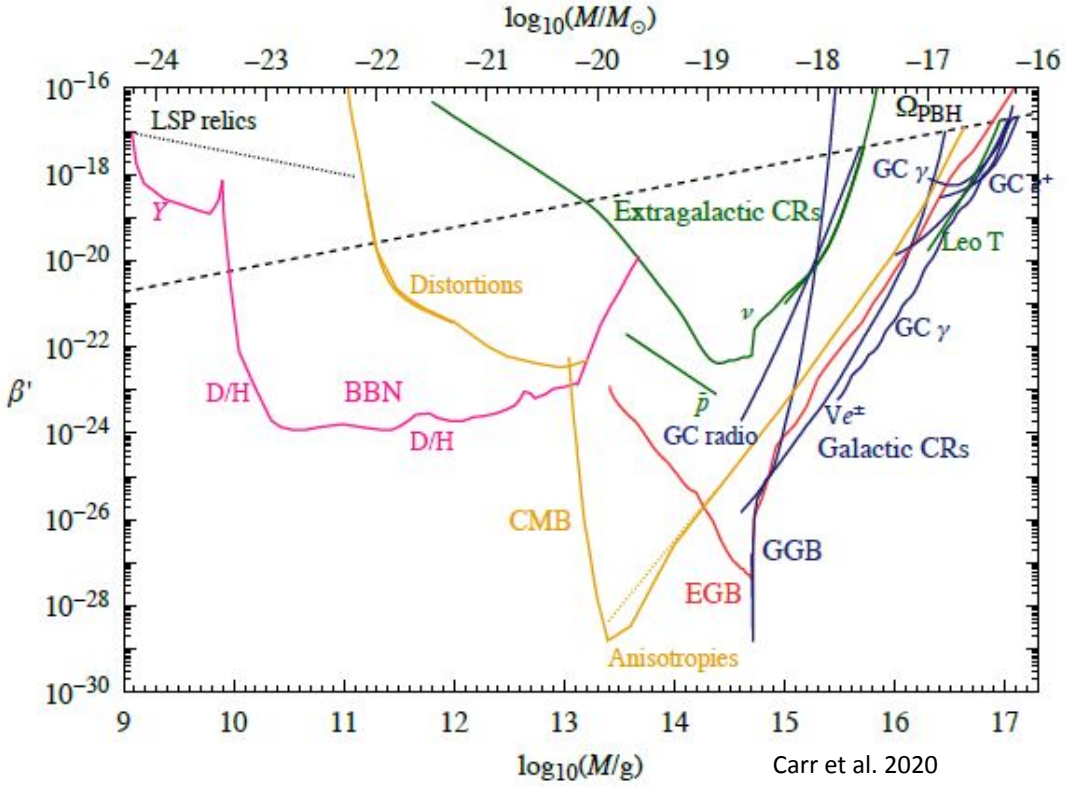
Natural consequence of inflation*

Formation scenarios usually result in gravitational waves (NanoGRAV?)

Emits Hawking Radiation

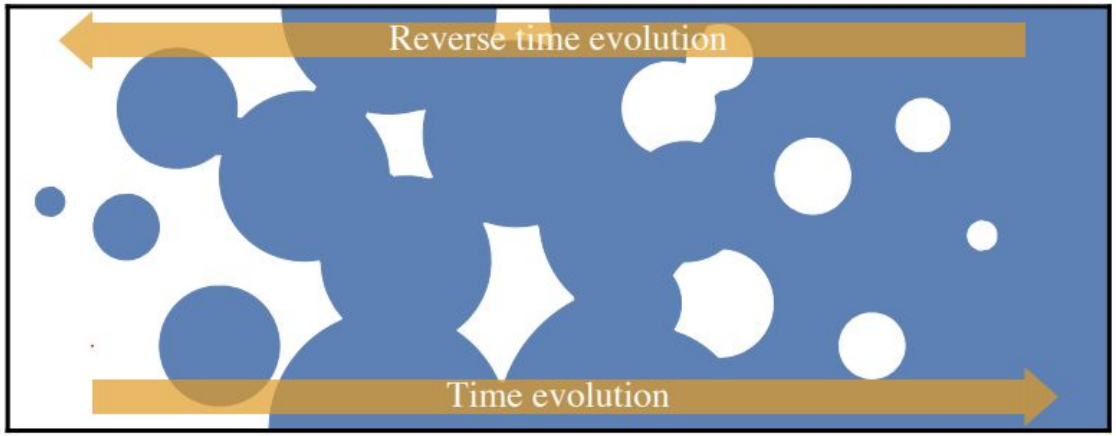
space.com

Light PBH Bounds

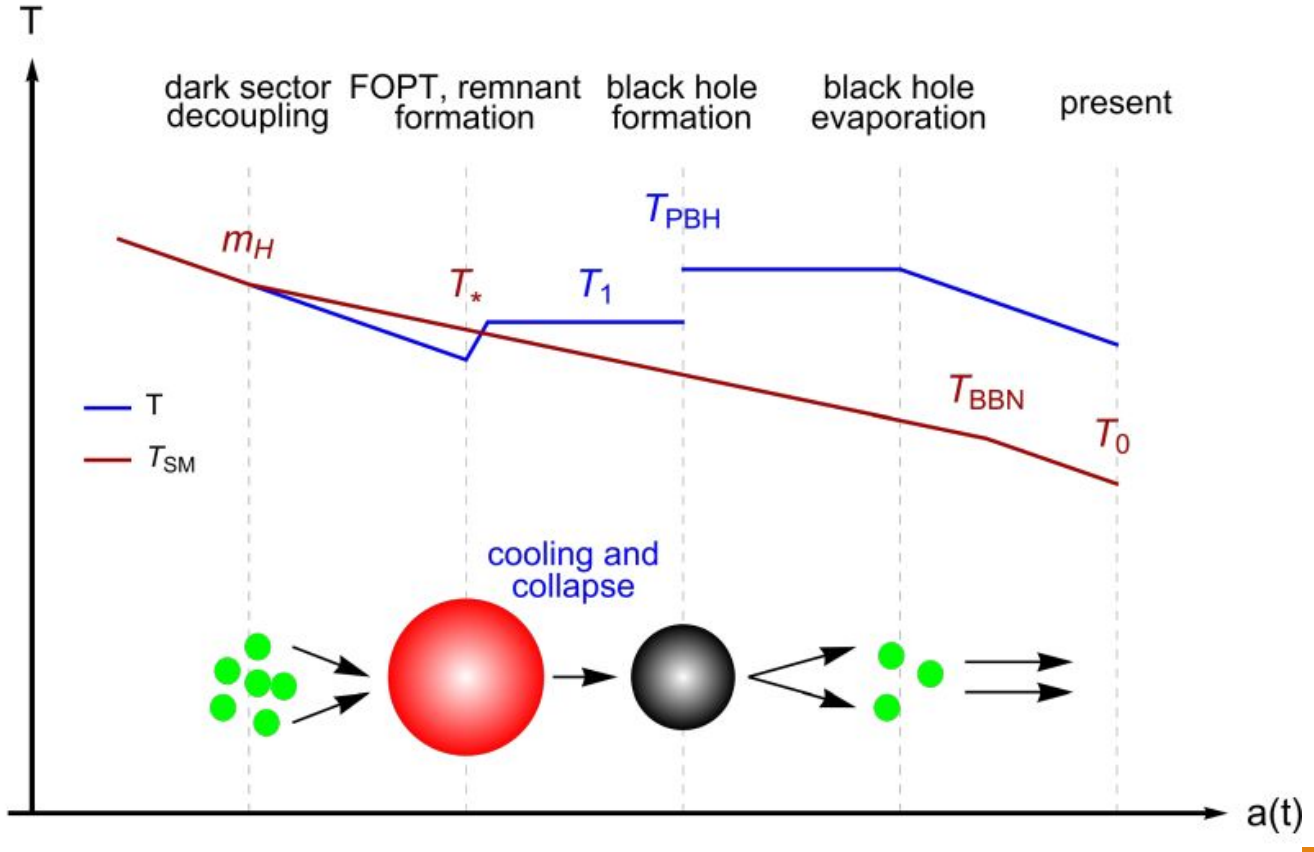


Carr et al. 2020

Primordial Black Holes from Dark Particles



Timeline


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

Dark Sector Model

Simple model with (asymmetric) fermion and scalar

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

Higgs portal and Yukawa terms

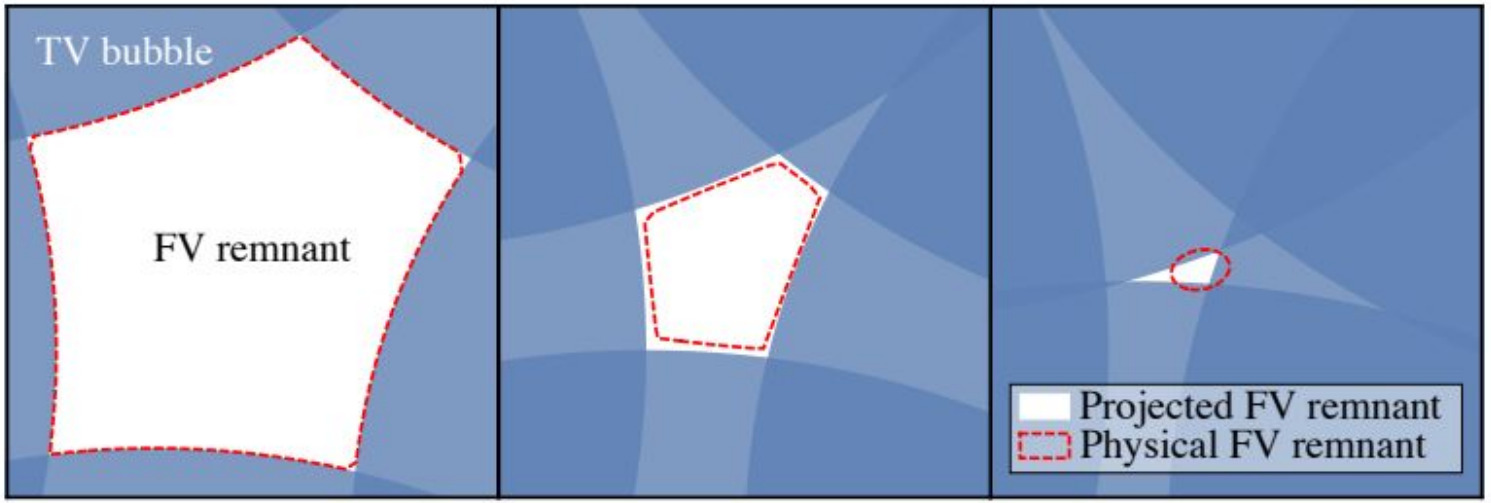
Particle trapping:

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

Initial Collapse

True bubble walls expand

Trapped particles confined to compact remnants



SM Portal Cooling

Thermal balls support by thermal pressure against vacuum pressure

Trapped φ particles annihilate through Higgs coupling

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

Cooling leads to thermal ball ->Fermi ball transition (Fermi Pressure)

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

Cooling should end before BBN, lower bound on coupling

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

Light 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

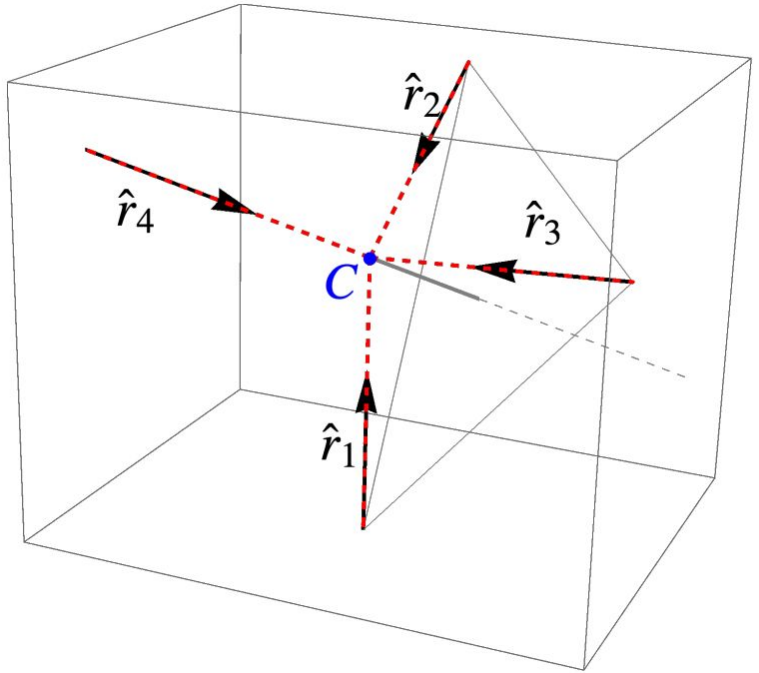
- Kept at constant temperature
- Semi-stable DM

Fermi Balls

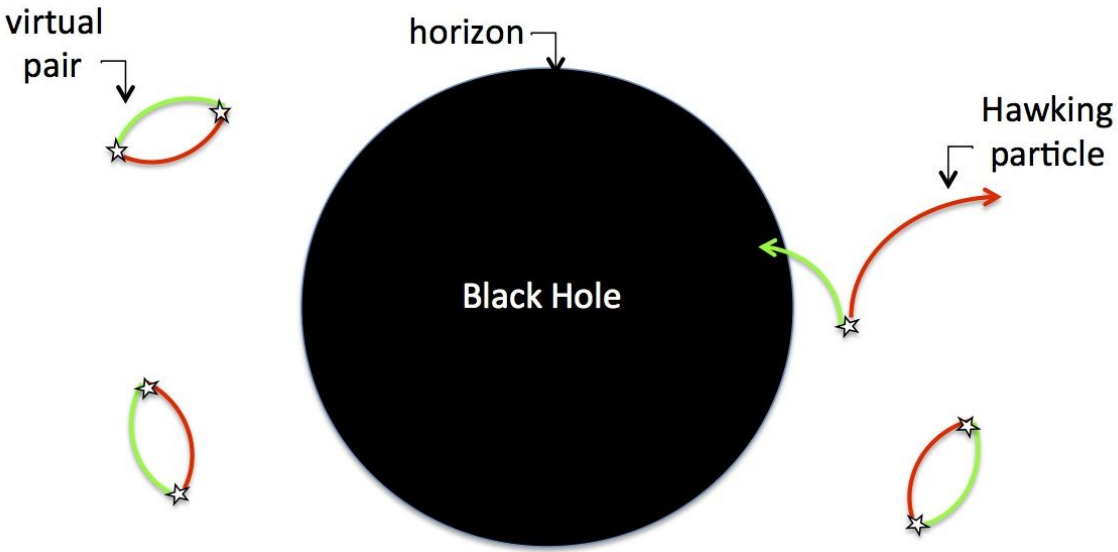
- Mass from fermion asymmetry
- Unstable with strong Yukawa force

Primordial Black Holes

- Can efficiently form accretion disks
- Hawking radiation



Dark Particles from Primordial Black Holes



Eurekasparks.org

Evaporating PBH

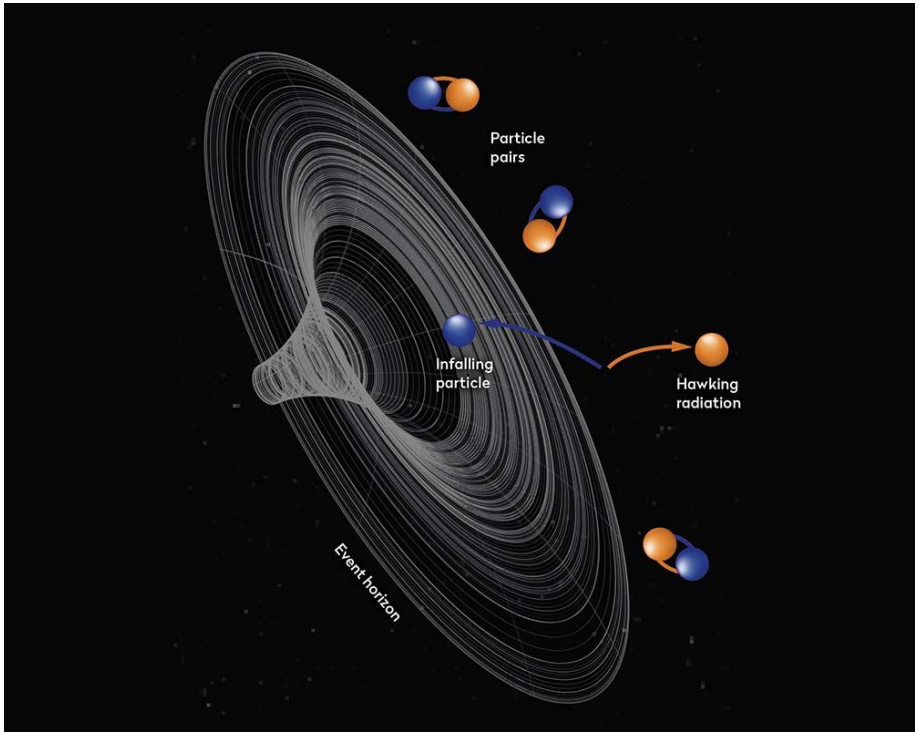
Recent interest on very light PBH

Hawking Temperature

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

Hawking evaporation emits particles based on mass-> DM emission

What if DM produced PBH that produced DM?



Getty Images

PBH Domination

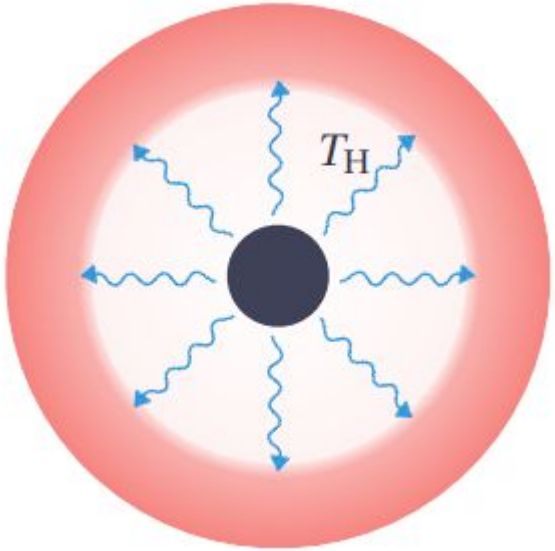
PBH density grows relative to plasma density

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

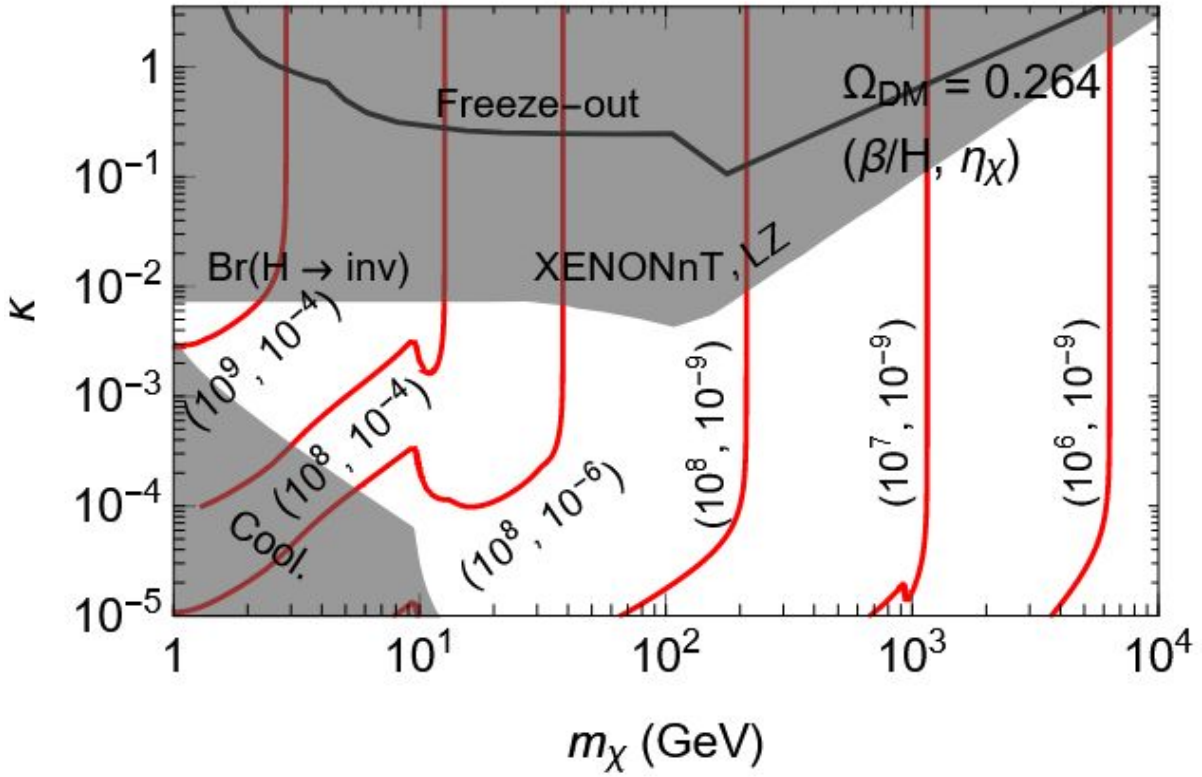
BBN constraints on FOPT/cooling/evaporation timescale

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

Direct detection experiments (XenonNT, LZ)

Invisible Higgs Decays (LHC)

WIMP Regurgitation



Conclusions

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

2. The three endpoints of this process, thermal balls, Fermi balls, and PBH can all be dark matter candidates.

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.