

PBH Mergers  
in  
PBH Clusters  
during  
PBH Domination  
in the  
Early Universe

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⚠ WORK IN PROGRESS ⚠

Early Universe

> PBH Domination

>

PBH Clusters

>

PBH Mergers

Primordial Black Holes are a generic prediction of many theories, forming in the very early universe rather than via stellar collapse

### Motivations

- PBH dark matter
- SMBH seeds
- Gravitational waves

### Formation Mechanisms

- Collapse of overdensities produced by inflation
- Topological defects
- and many more...

We are agnostic regarding the PBH formation mechanism

Early Universe

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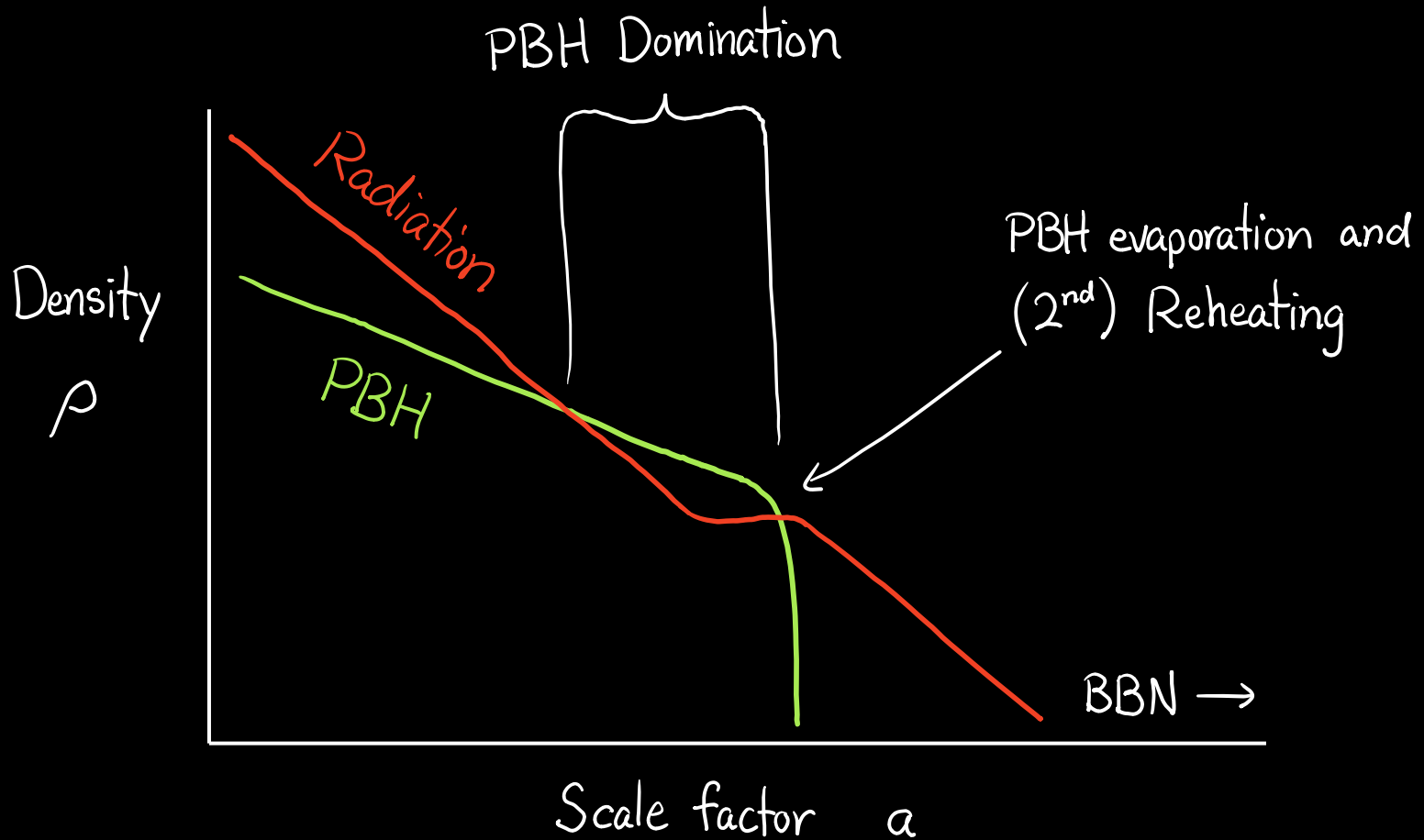
PBH Domination

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PBH Clusters

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PBH Mergers



Early Universe

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PBH Domination

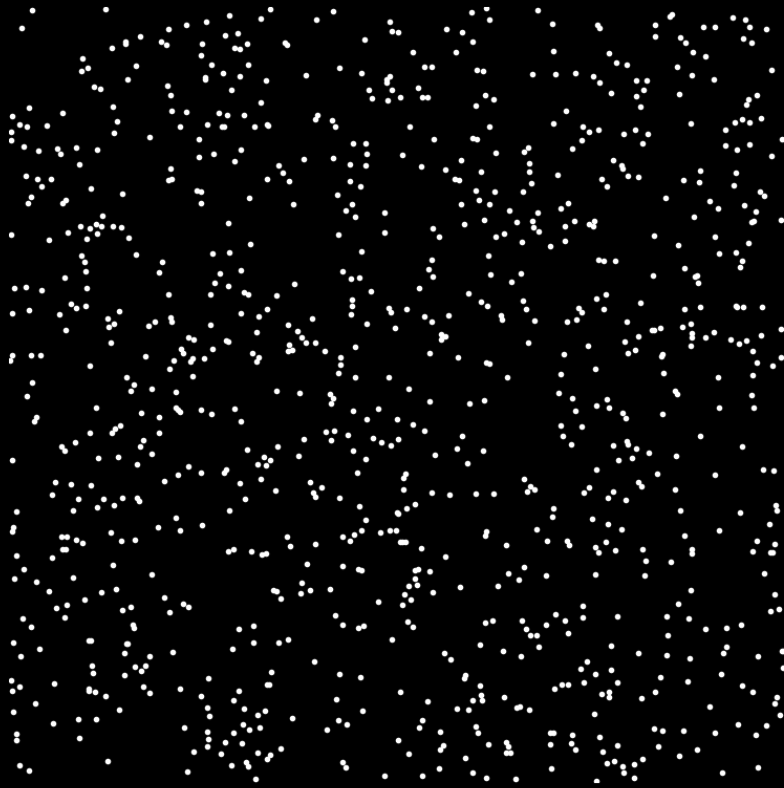
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PBH Clusters

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PBH Mergers

Shot noise (from random spatial distribution) is an unavoidable source of fluctuations and structure — we consider this minimal scenario



Shot noise power spectrum

$$P_{\text{BH}}(k) = \frac{1}{n}$$

Average number density

Fluctuations grow in PBH domination

$$\delta(a) \propto a$$

eventually forming PBH clusters

Early Universe

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PBH Domination

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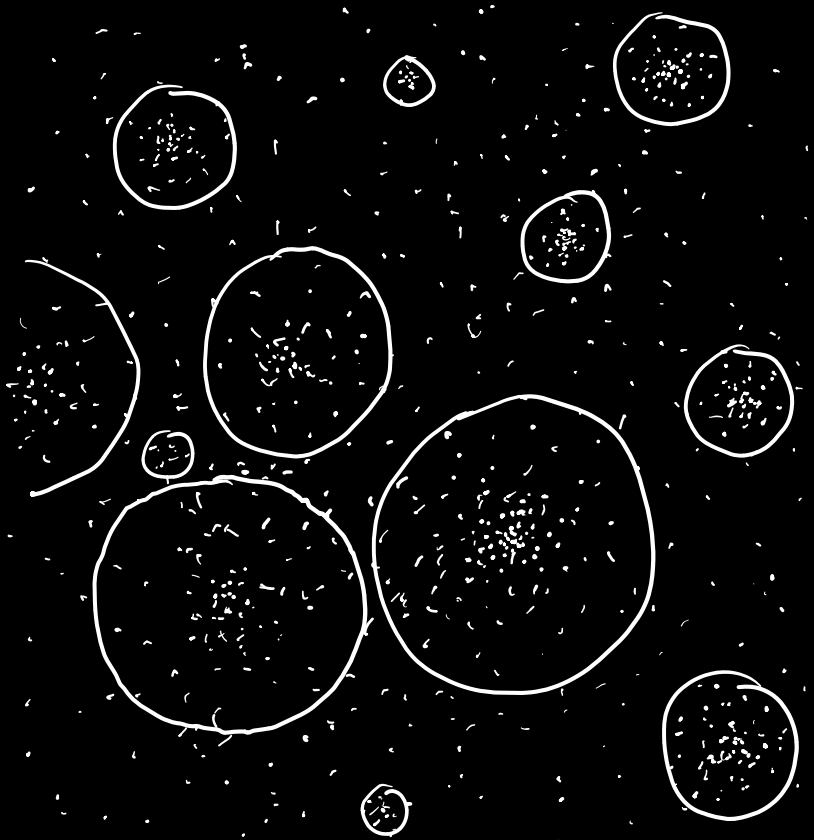
PBH Clusters

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PBH Mergers

[Press + Schechter 1974]

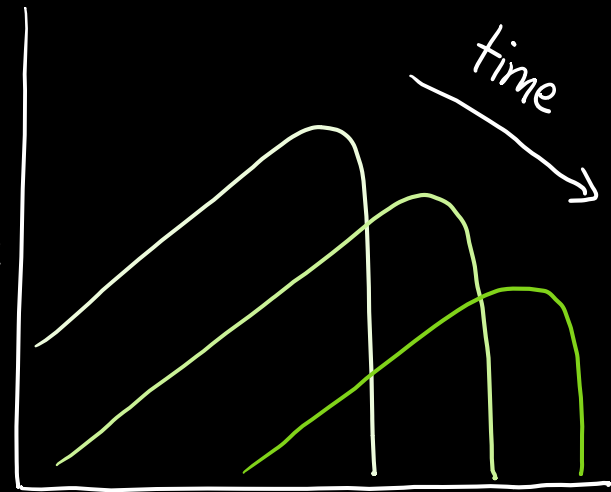
Press-Schechter formalism describes formation and growth of clusters



$$P(k) \rightarrow \frac{dn}{dM}$$

Cluster mass distribution

$$M^2 \frac{dn}{dM}$$



Cluster mass  $M$

# Dynamics inside PBH clusters

(all of these dissipate energy)

## Binary mergers

Encounter



Capture



Inspiral

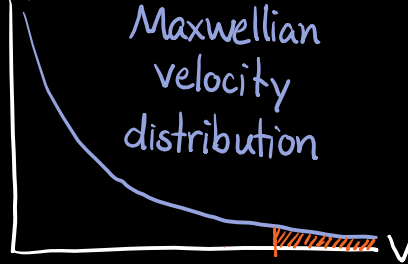


Turner 1977

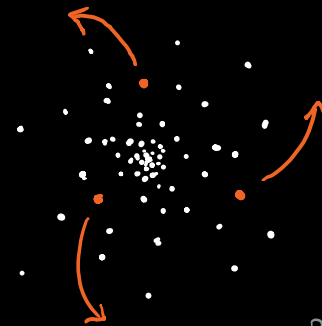
## Cluster evaporation

$f(v)$

Maxwellian  
velocity  
distribution

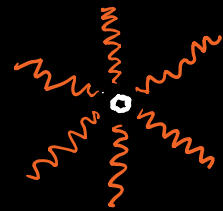
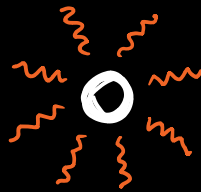
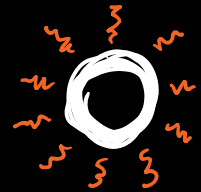


escape  
velocity



Binney + Tremaine

## Hawking evaporation



Hawking 1974

Difficult to study without N-body simulation

Early Universe

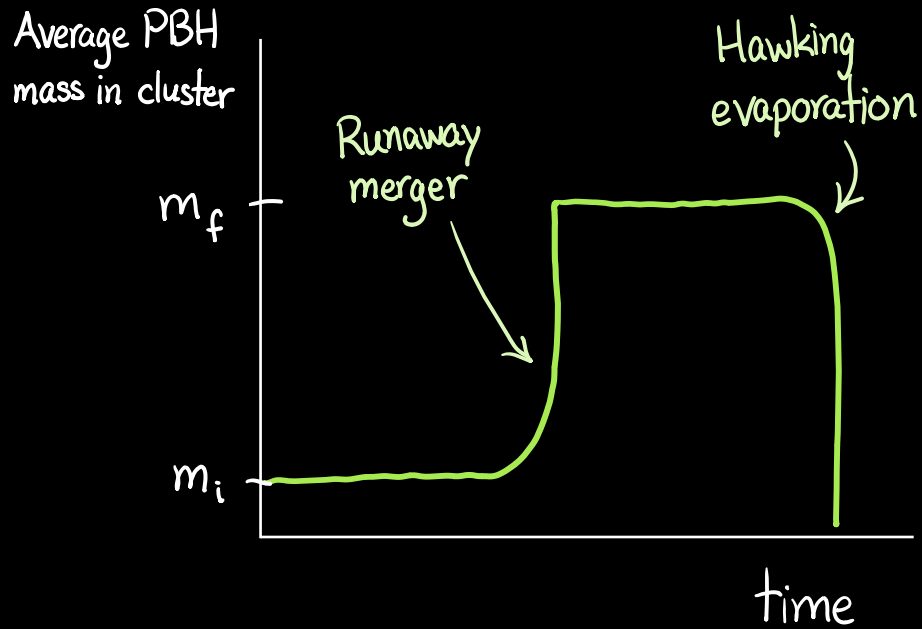
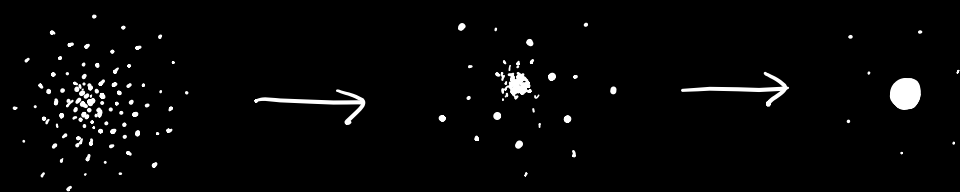
> PBH Domination

> PBH Clusters

>

**PBH Mergers**

Internal cluster dynamics lead to collapse and runaway merger to a single BH



Fraction of cluster mass that collapses to single BH

$f_{col}$

$$= \left( \frac{\Gamma_{ce}}{\Gamma_{mrg}} \right)^{\frac{7}{5}}$$

Cluster evaporation rate

Merger rate

# Free Parameters

$m_i$  Initial PBH mass

$t_i$  Time when PBH fluctuations start to grow

Can be mapped onto your favorite formation mechanism

# Sensible Constraints

- Reheating temperature  $> T_{\text{BBN}}$

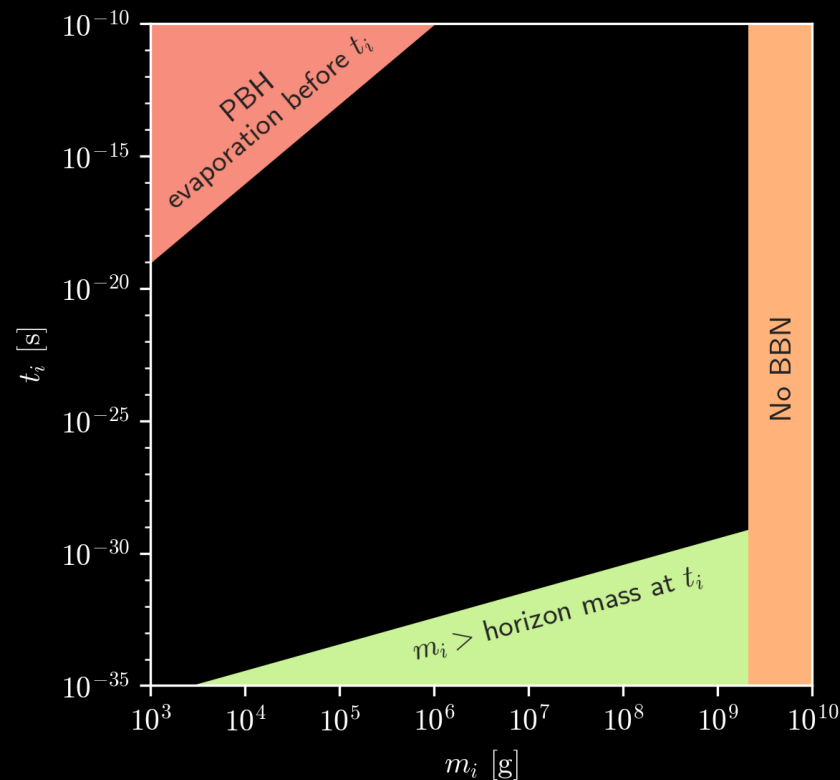
$$\hookrightarrow m_i \lesssim 10^9 \text{ g}$$

- No PBH evaporation before  $t_i$

$$\hookrightarrow t_i \lesssim 1 \text{ s} \left( \frac{m_i}{10^9 \text{ g}} \right)^3$$

- Causality: Horizon mass at  $t_i > m_i$

$$\hookrightarrow t_i \gtrsim 10^{-30} \text{ s} \left( \frac{m_i}{10^9 \text{ g}} \right)$$

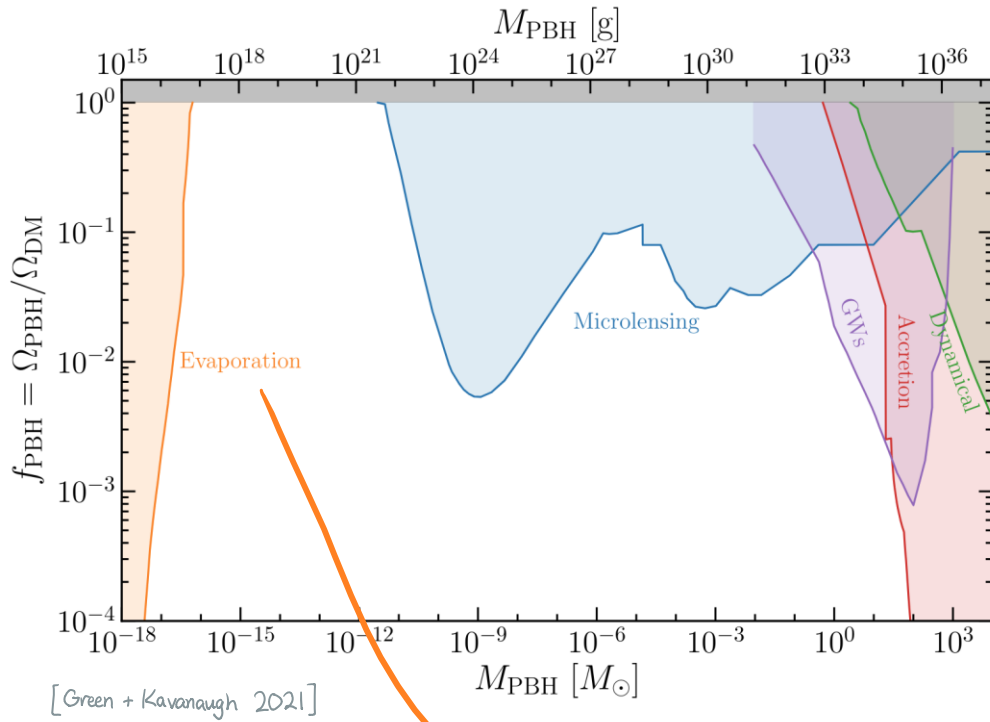




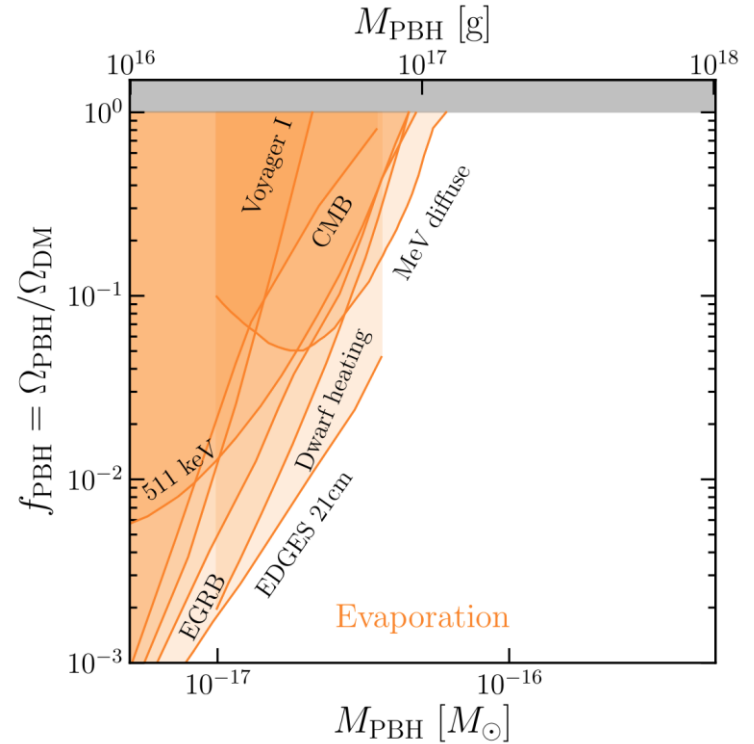
# Can PBH mergers build PBH dark matter?

$\sim 10^9 \text{ g} \xrightarrow{\text{mergers}} \sim 10^{17} \text{ g}$

to build stable PBH dark matter



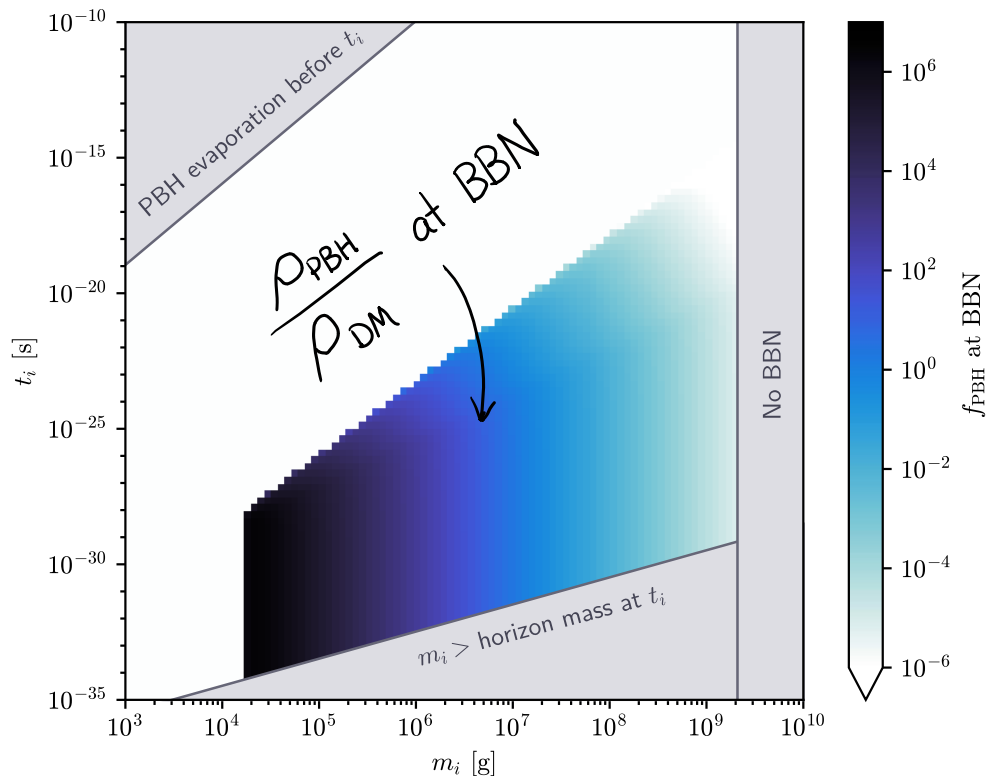
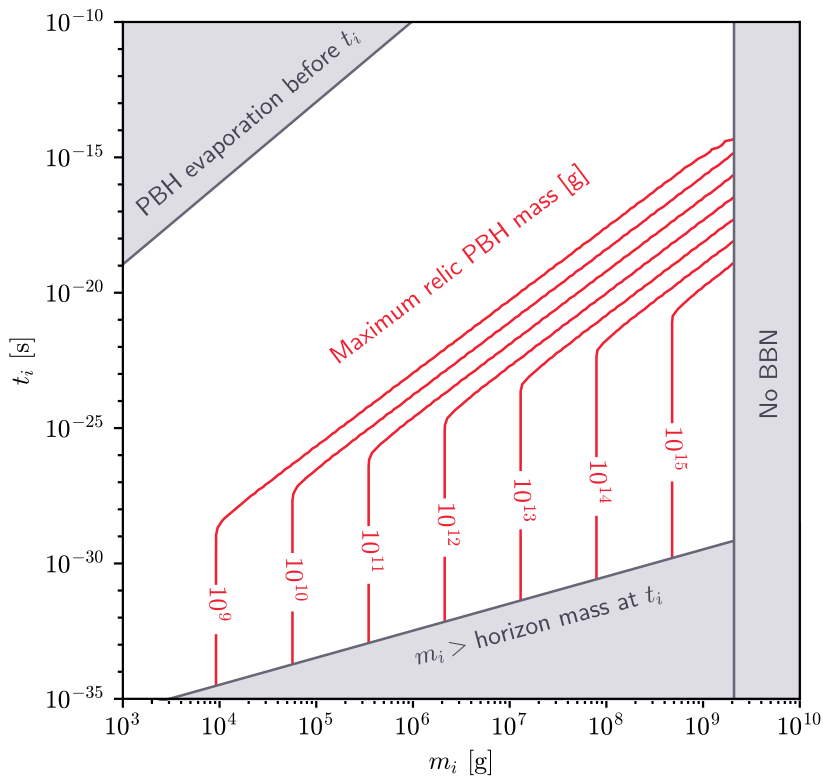
detailed view



# Constraints on relic merged PBHs

Relic PBH mass typically evaporates before today

Very large evaporating PBH abundance could inject too much energy during BBN, CMB, etc.



# TAKEAWAYS

Clustering is an unavoidable consequence of PBH domination and it leads to runaway mergers

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Due to mergers, PBHs that would otherwise be unobservable can survive longer and have observable consequences  
(but probably not long enough to be dark matter)

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N-body simulations needed to confirm cluster dynamics

but perhaps with enhanced clustering...

PBH Dark Matter

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