Building Dark Structure in an Early Matter Dominated Era

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In Collaboration with J Leo Kim, Joe Bramante, Chris Cappiello, Qinrui Liu, and Aaron Vincent

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Queen's University

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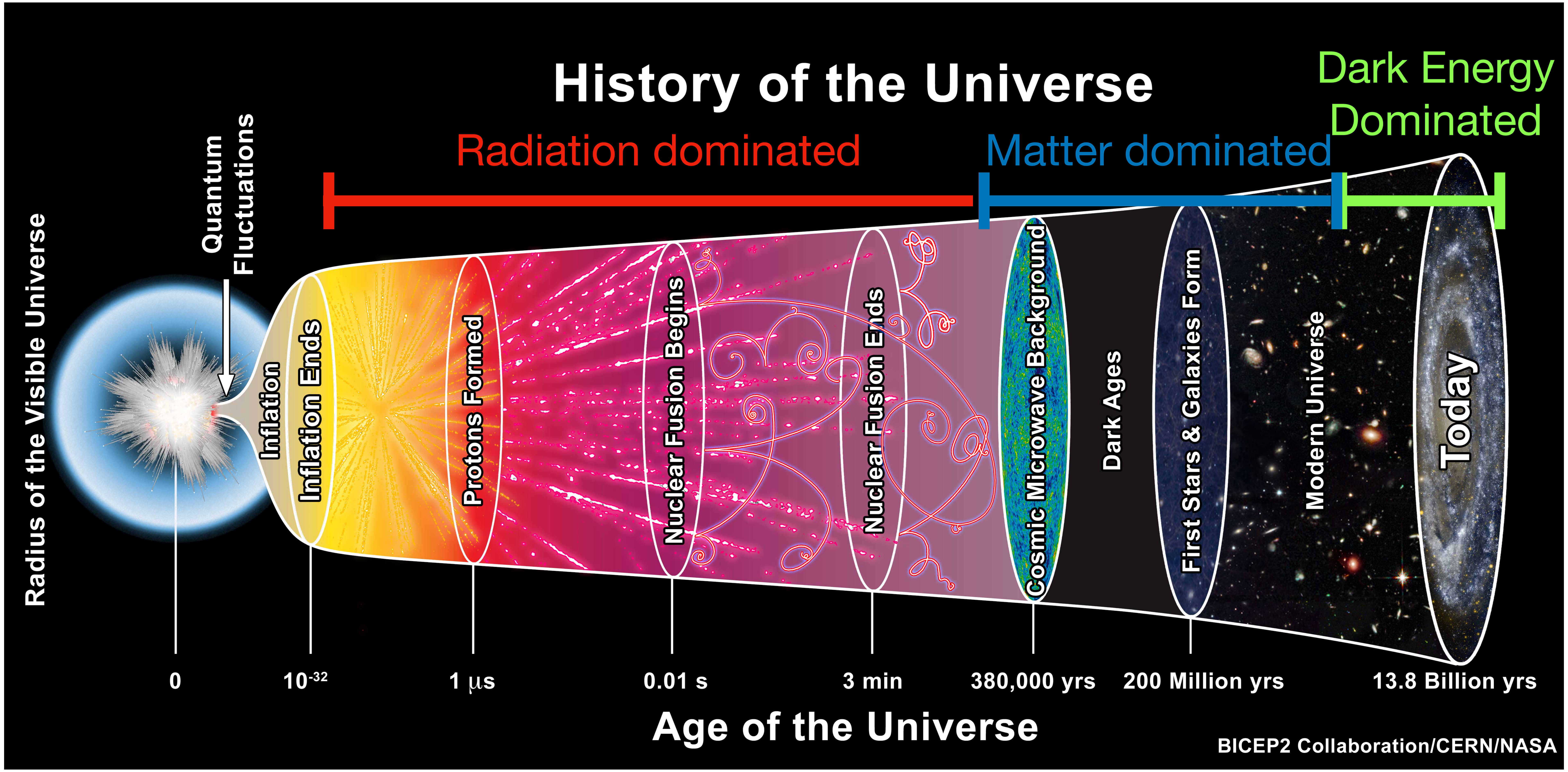
TeVPa August 29 2024

What happens when we allow a dissipative dark sector to dominate *before* BBN?



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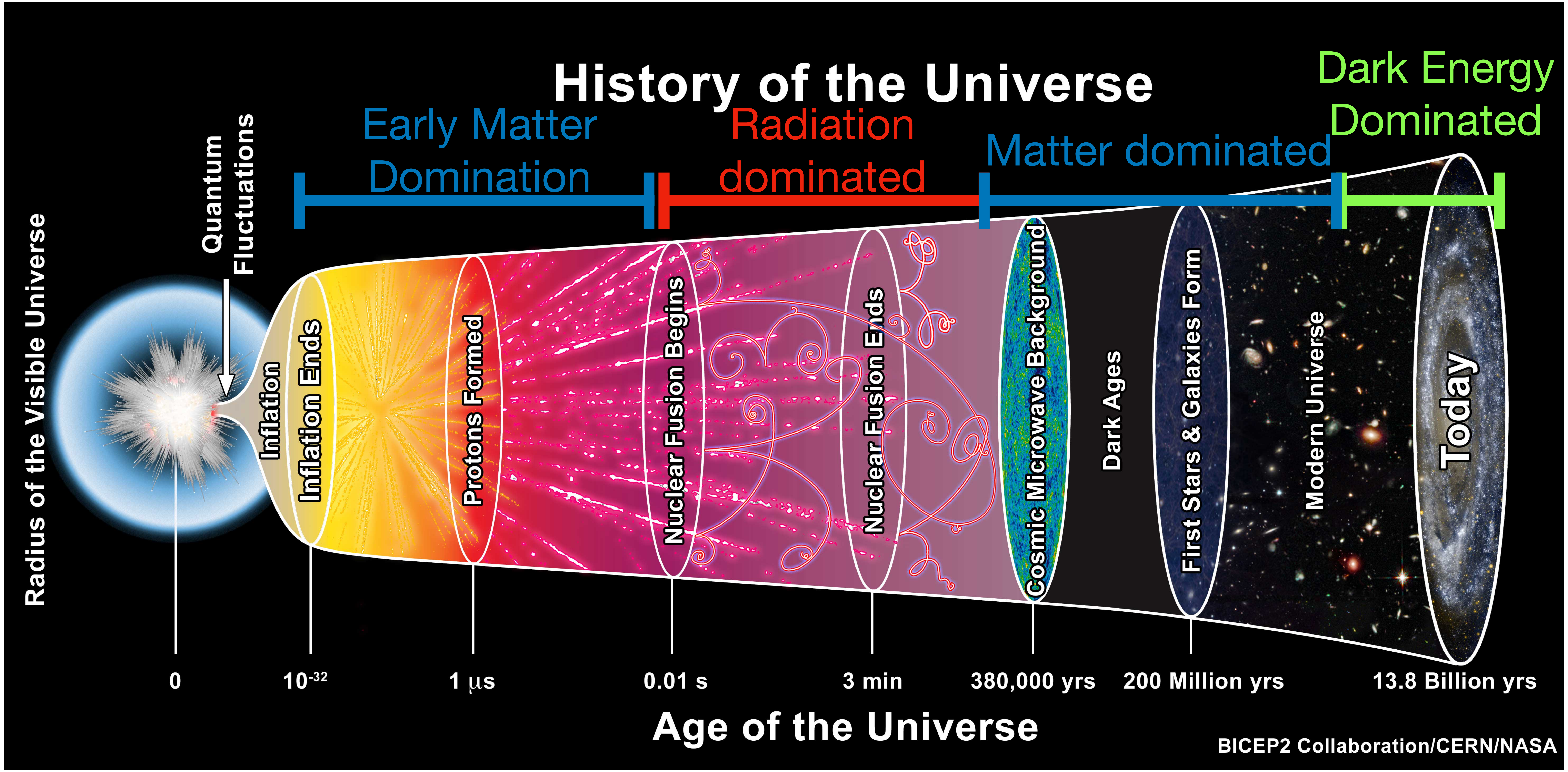
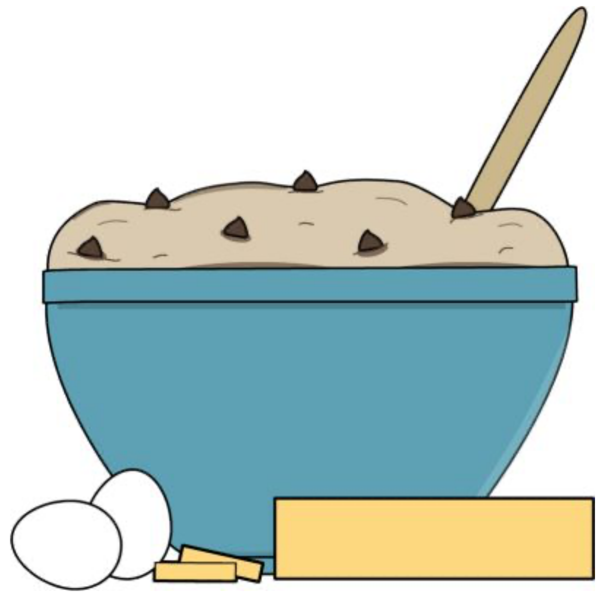


We found…

- A new mechanism to produce dark compact objects
- A new way to form primordial black holes
- Late time collapse into low mass black holes
- Late time decay of low mass black holes
- Dissipative dark sector can be all of dark matter
- Dark halo size set by features of the dark matter model

Key Ingredients



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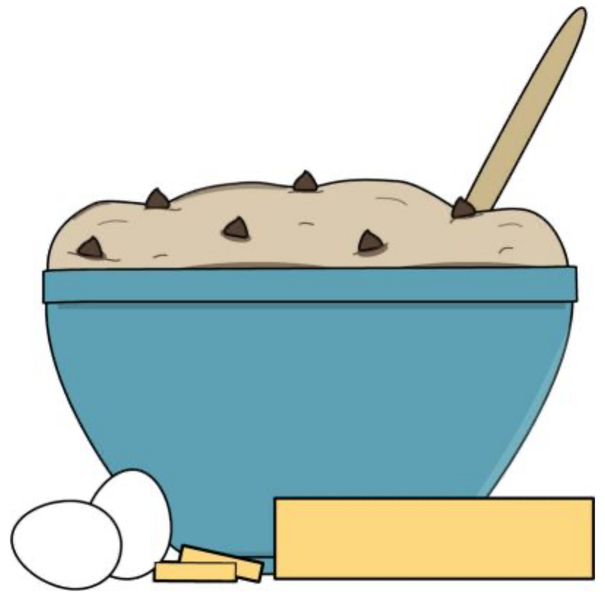

Dark particle to dominate the energy density of the Universe

$$\chi$$

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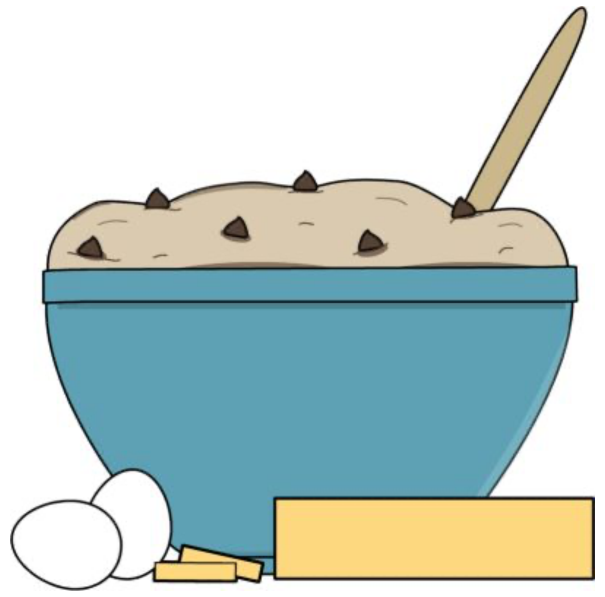

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"Dark electron"

$m_\chi > 10^4$ GeV

Asymmetric fermion

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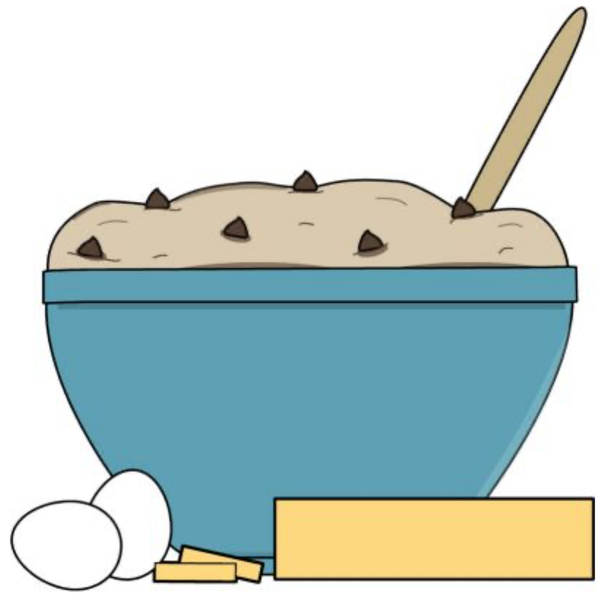

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Dark mediator to dissipate energy and help with structure collapse

$$\gamma_D$$

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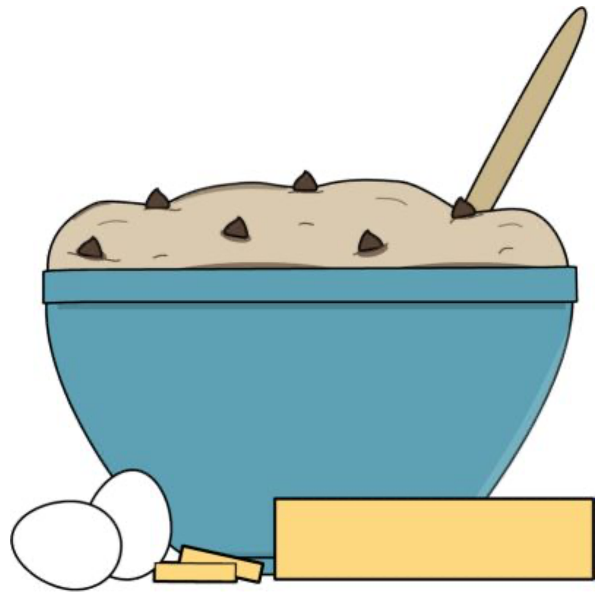

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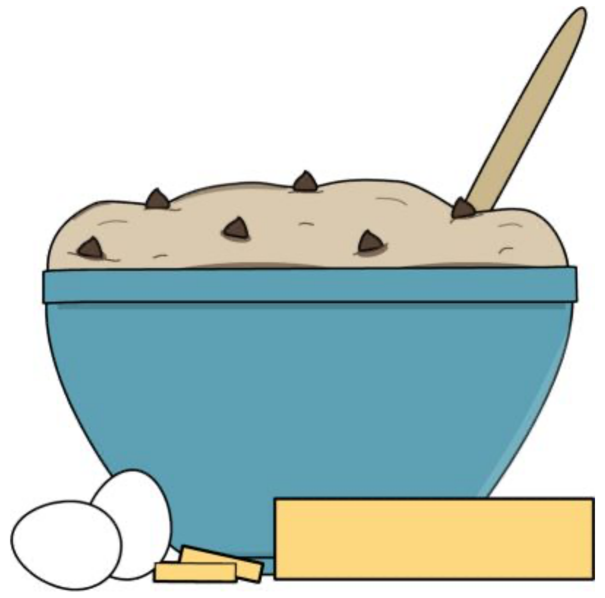

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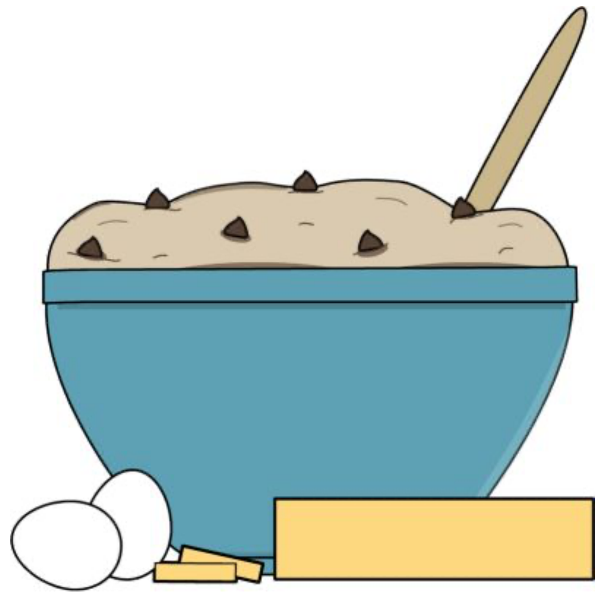

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An exit strategy to return the universe to radiation domination

Quick period of thermal inflation

Rapid expansion dilutes χ

Field decays to standard model

The dark sector model

$$\mathscr{L} \supset \bar{\chi}(i\gamma^\mu D_\mu - m_\chi)\chi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_{\gamma_D}^2 A_\mu A^\mu$$

$$D_\mu = \partial_\mu - i4\pi\alpha_D^{1/2}A_\mu$$

Original model in Chang et al 2019

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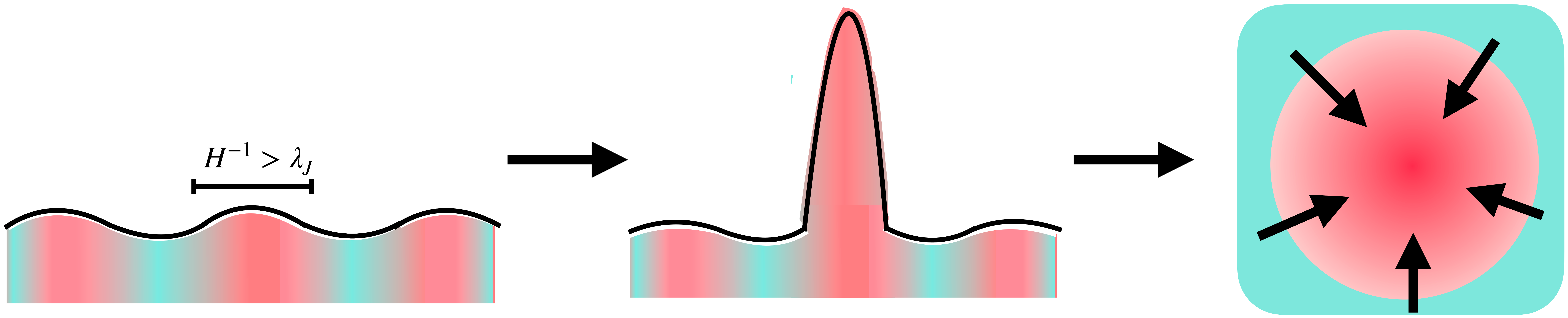
Scalar field potential for thermal inflation

$$V(\phi) = V_0 - \frac{1}{2}m_\phi^2|\phi|^2 + T^2|\phi|^2 + \dots$$

Formation of Dark Compact Objects

Evolution of dark electron halos during early matter domination



Perturbations enter the horizon and begin growing when Jean's length less than Hubble length

Slight over densities grow linearly with the expansion of the universe

Once density contrast ~ 1 overdense regions begin to collapse and virialize

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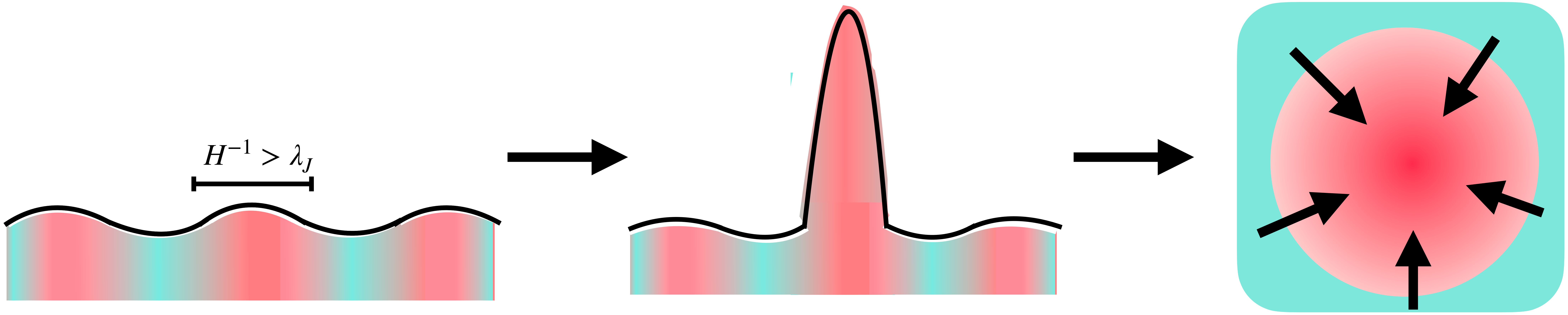

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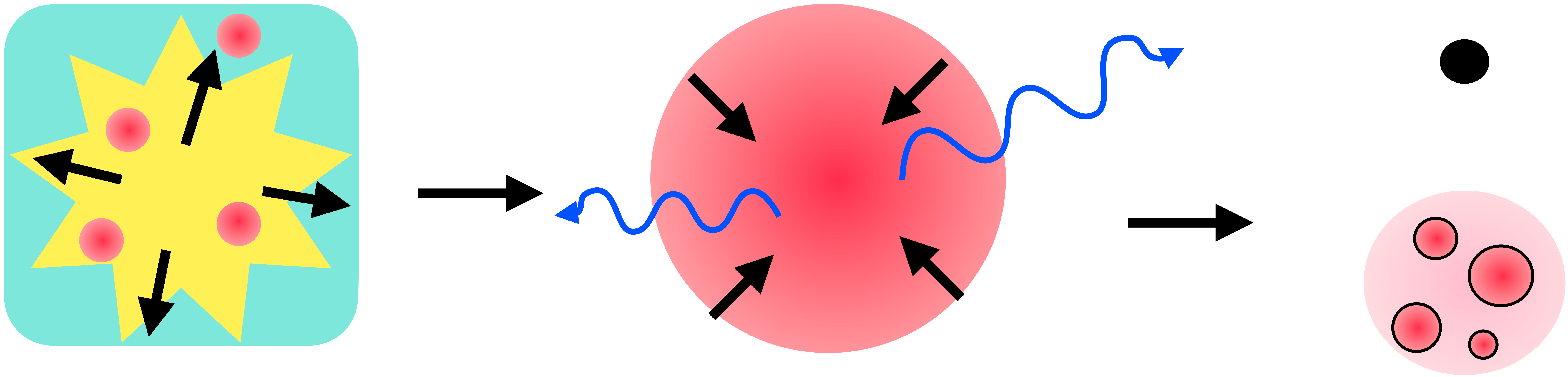
Returning to Standard Cosmology

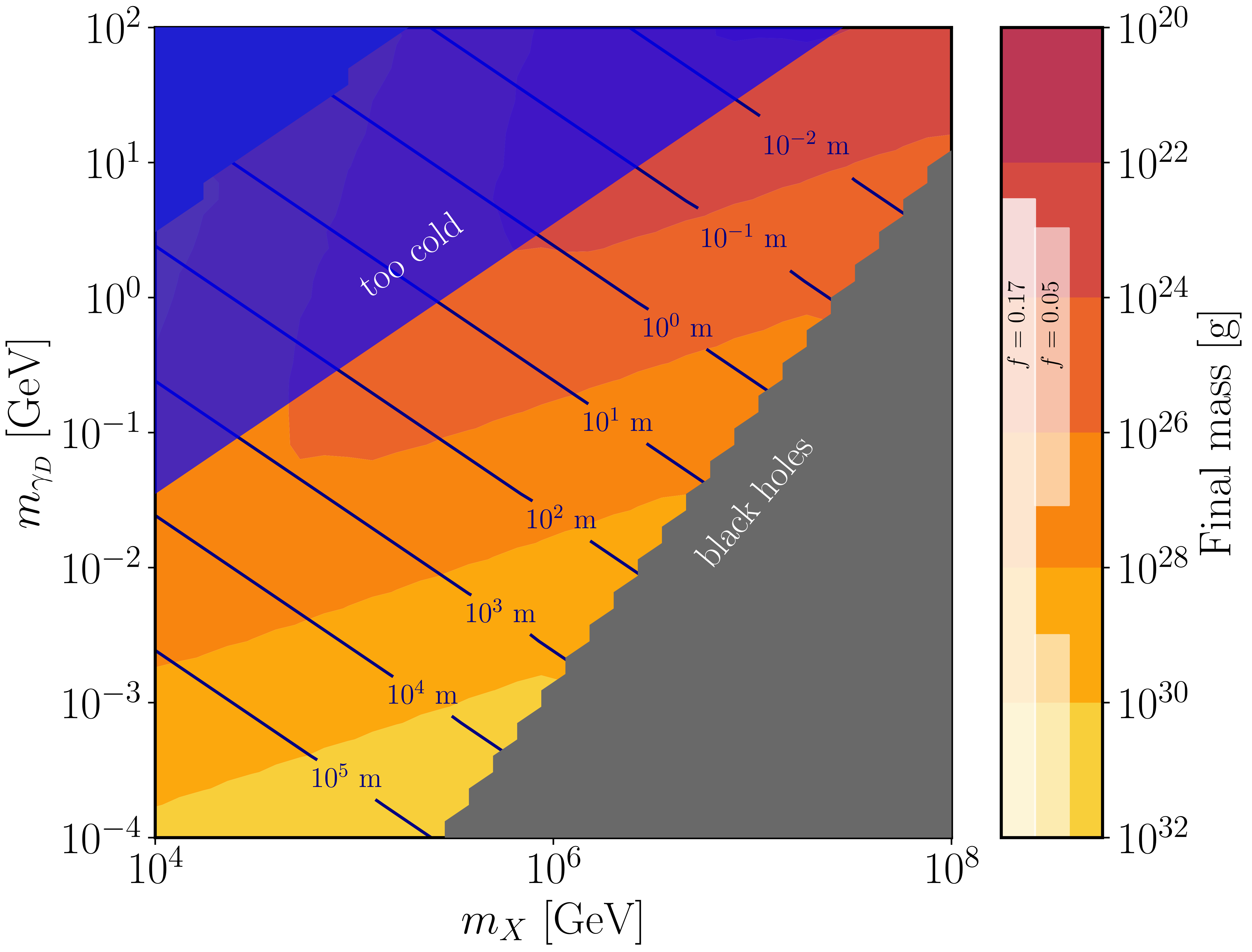


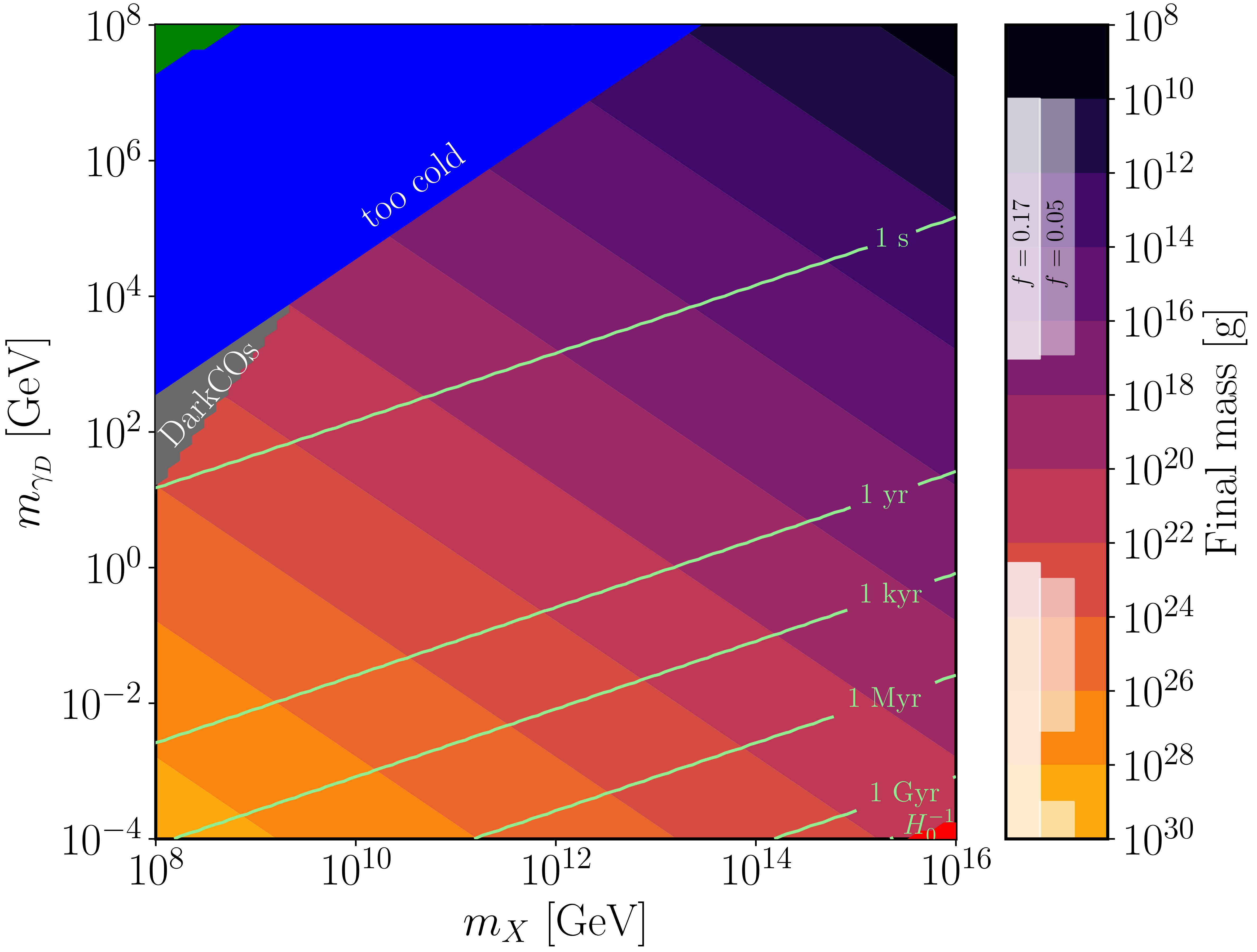
Thermal Inflation dilutes dark matter and returns universe to Standard model radiation domination

Halo continues to cool and compactly via dark bremsstrahlung

Halo collapses to a black hole or fragments into pressure supported dark compact objects

Final evolution of dark electron halos $\alpha_D = 0.1$ (zoomed in)





$\delta_0 \sim 10^{-5}$

Fragments **Black Holes**

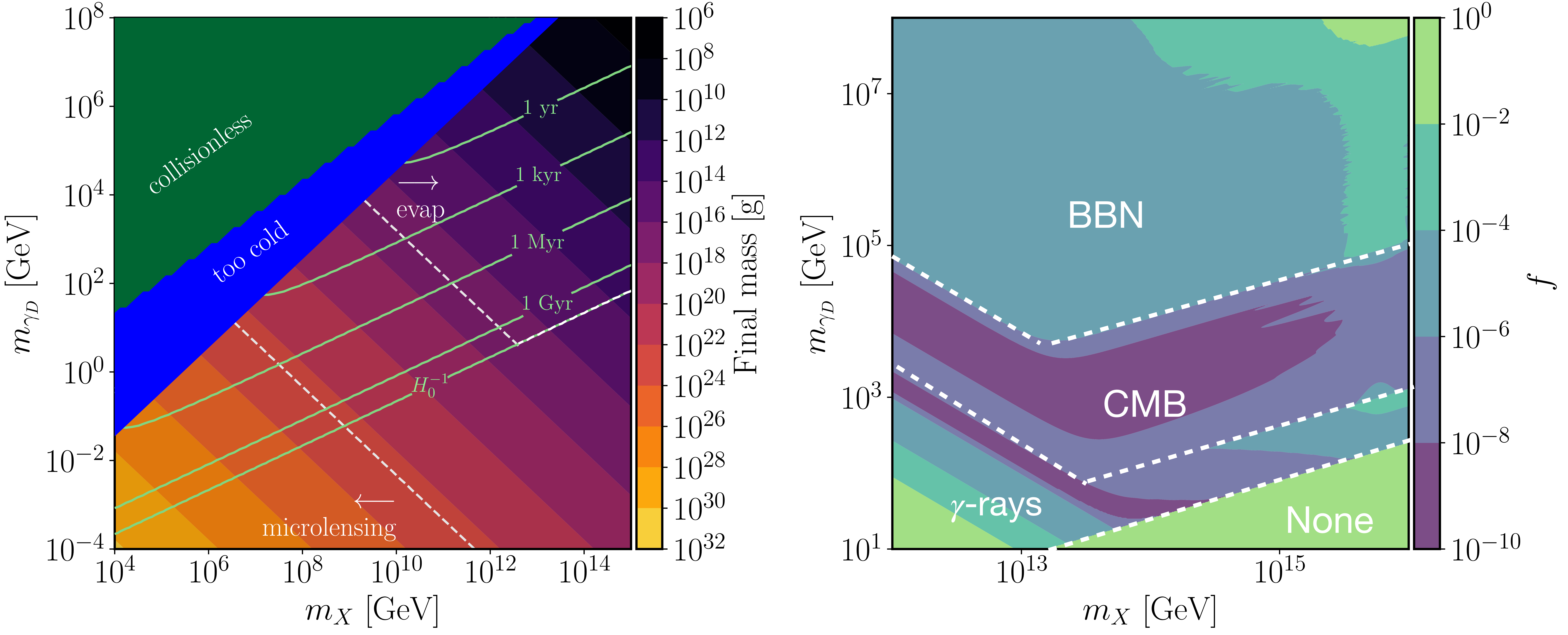
Delayed Primordial Black Holes

Reducing α_D slows cooling and collapse

Can lead to “late” collapse and evaporation of black holes

Delayed Primordial Black Holes??

$$\alpha_D = 10^{-7}$$

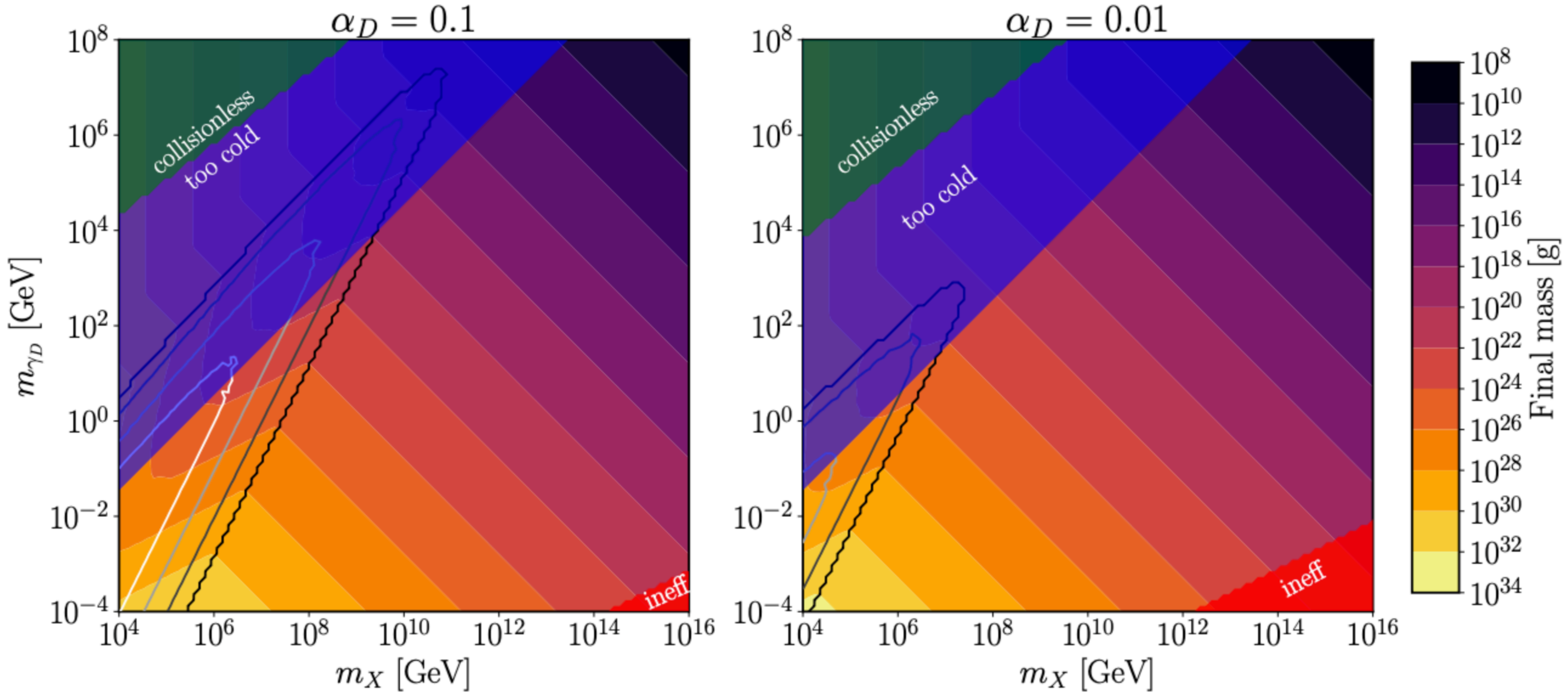


Conclusions

- Many of the tools used for star and galaxy formation are relevant to the dark sector once we introduce self interactions
- A dissipative dark sector can dominate the universe before BBN and lead to the creation of black holes and dark compact objects
- Predictions for the size and evolution of these objects follows straightforwardly from one's choice of dark matter model

Thank you for listening

Final evolution of dark electron halos



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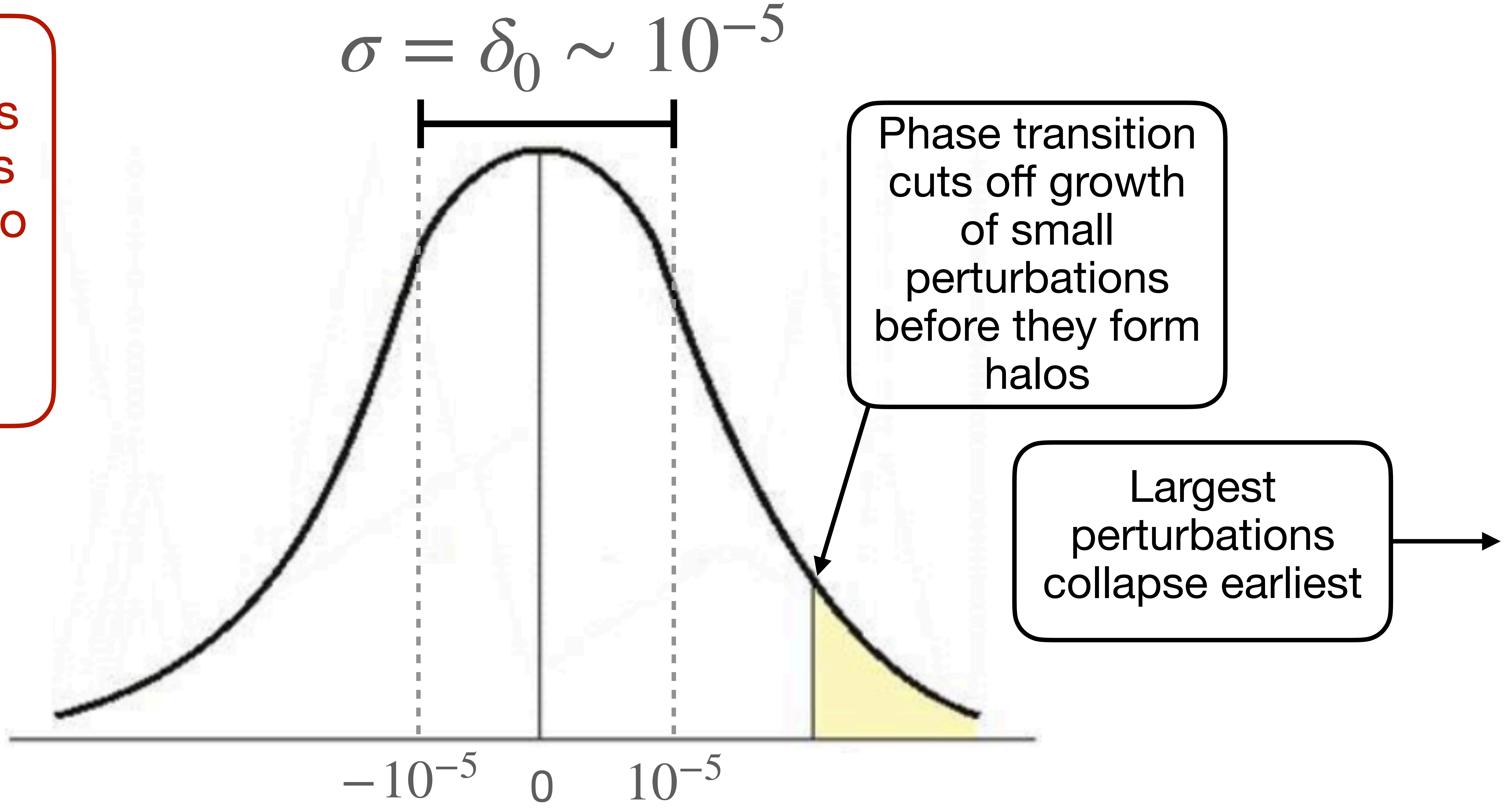
How much of the dark matter is in compact structure?

Answer: The fraction of mass in perturbations that have time to form halos before EMDE ends



Distribution of initial density perturbations δ_0

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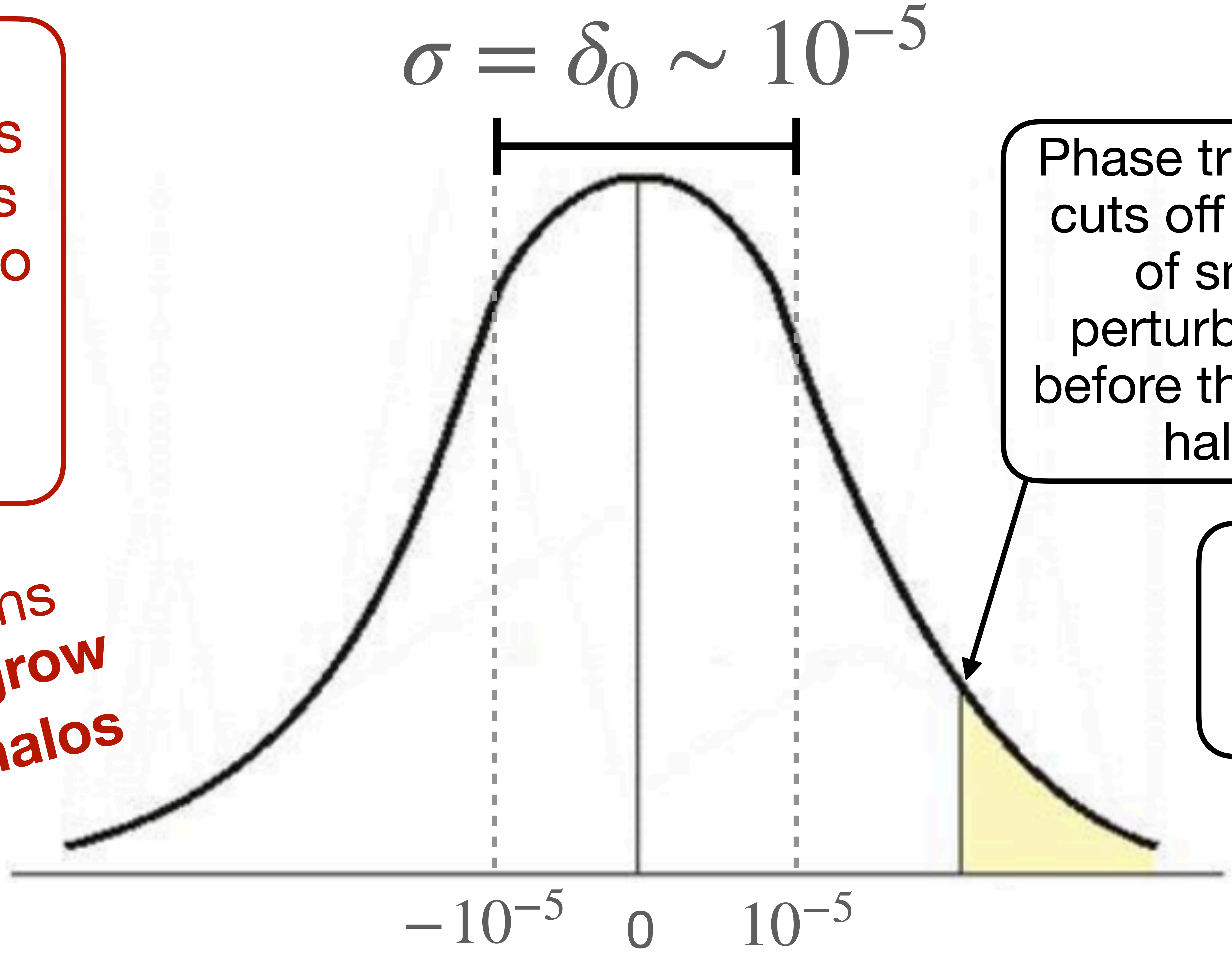


Distribution of initial density perturbations δ_0

Phase transition cuts off growth of small perturbations before they form halos

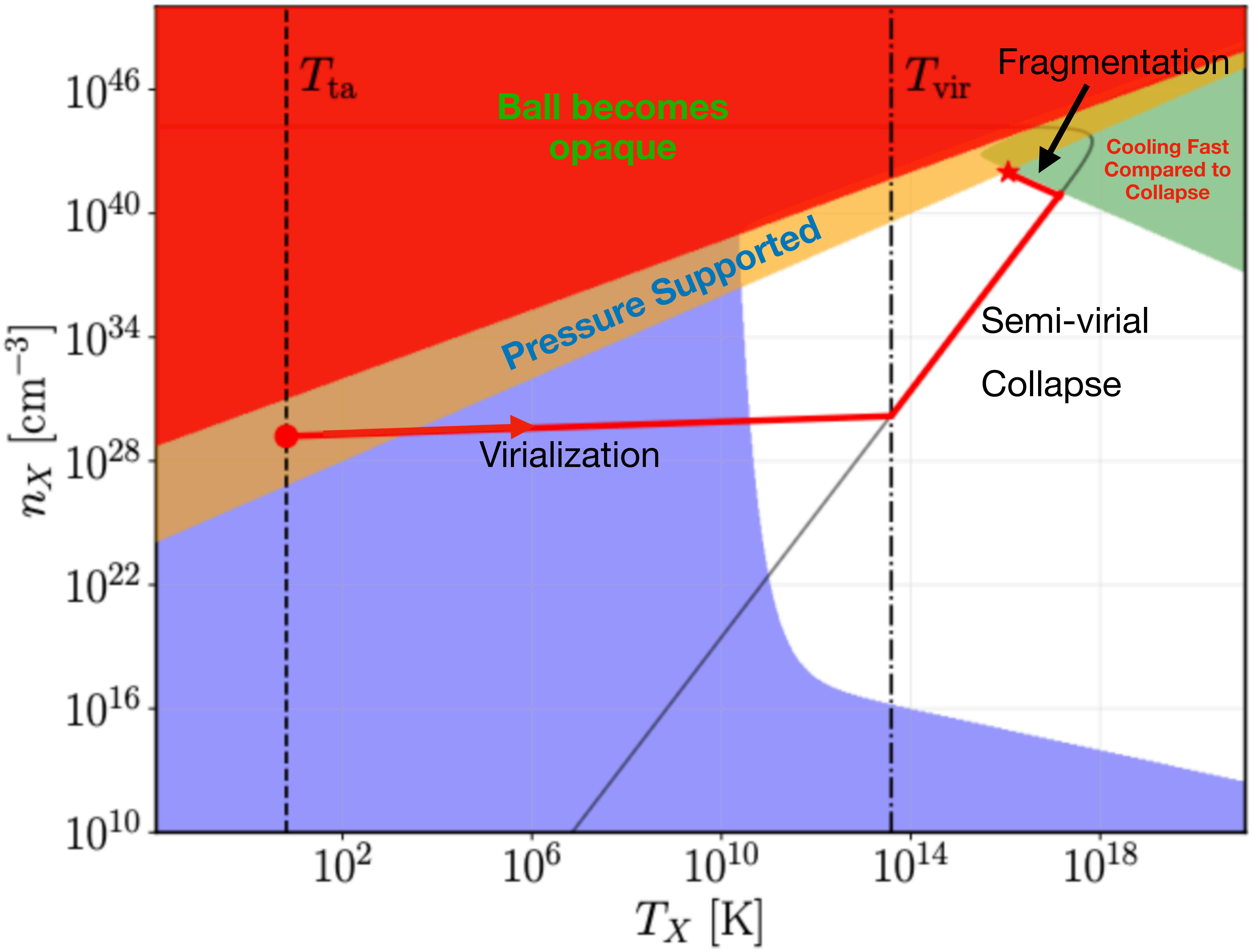
Largest perturbations collapse earliest

All perturbations over **1 STDeV grow** $\approx 17\,\%\ \chi$ **in halos**

Future work

- Press Schechter estimate of PBH / MACHO spectrum
- More careful treatment of fragmentation process
- Explore multiple matter domination “exit strategies”
- Include long range interaction case
- Explore impact of dark radiation emitted during collapse

Trajectory of an Example Halo



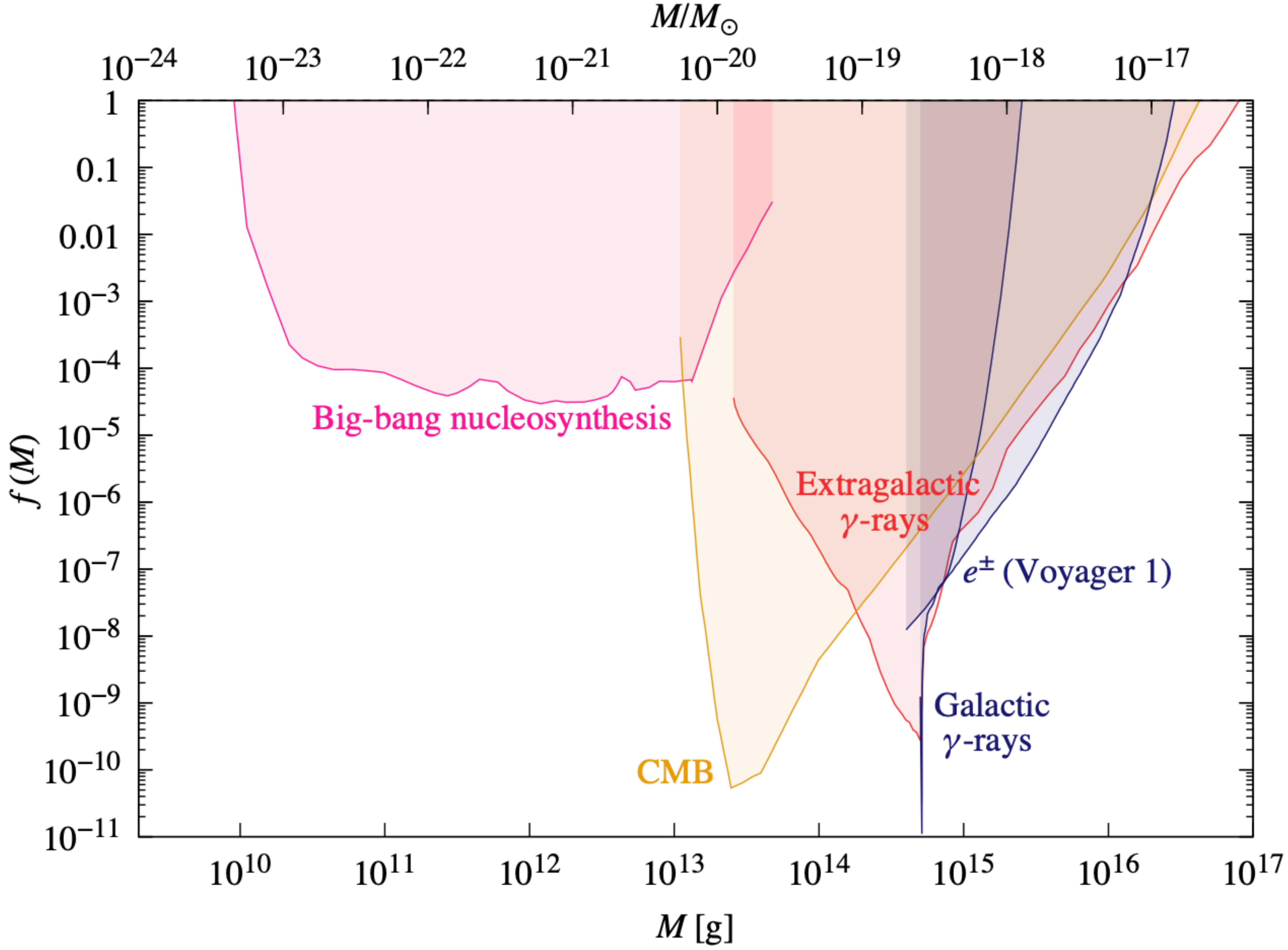
$m_x = 10^6$ GeV

$m_{\gamma D} = 10^{-1}$ GeV

$\alpha_D = 0.1$

$\delta_0 = 10^{-5}$

Limits on small black holes



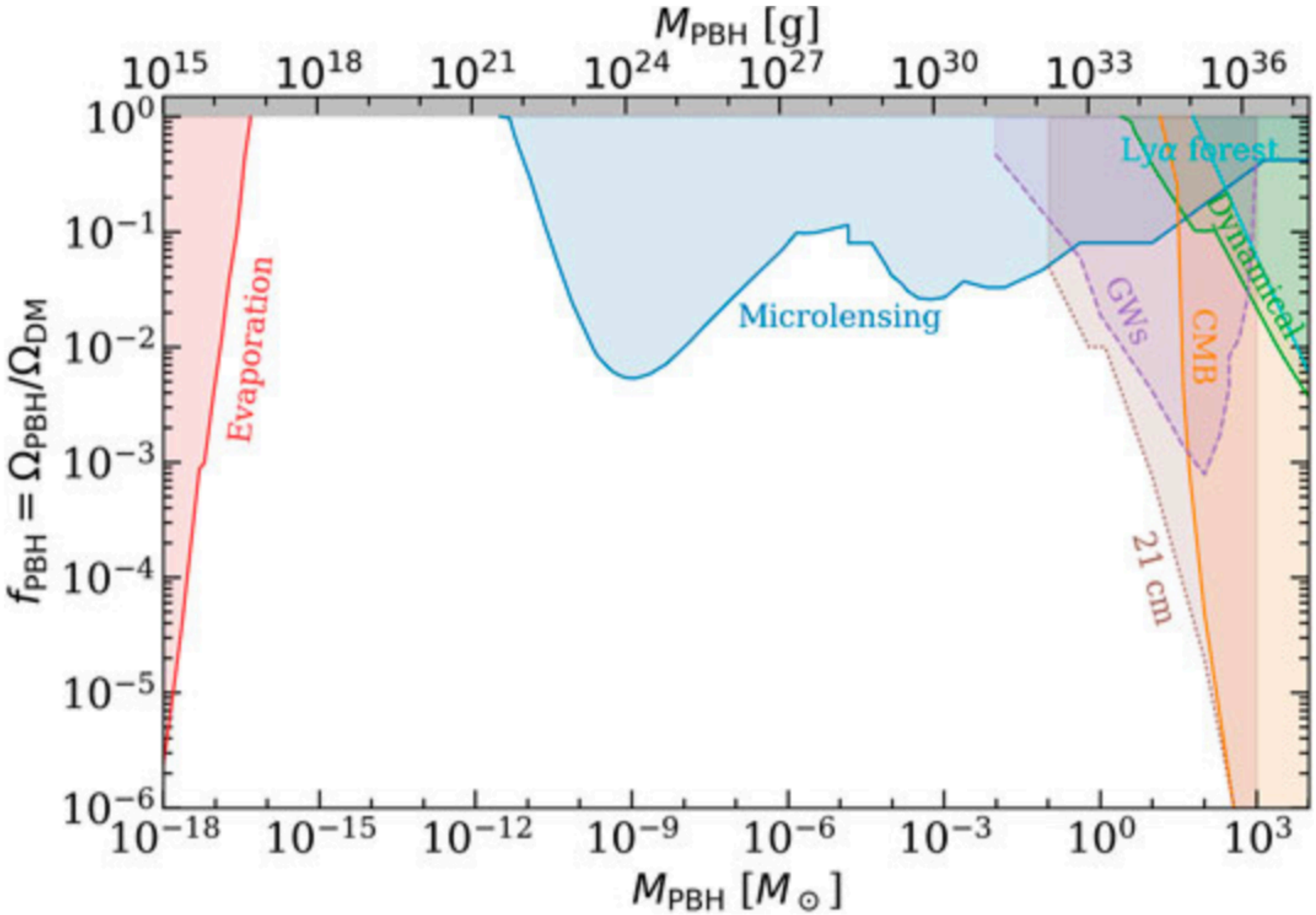
Black holes radiate + evaporate

Smaller black holes emit hotter radiation and evaporate faster

$m_{BH} \lesssim 10^{14}$g evaporate within the lifetime of the universe

Source: “Constraints on Primordial Black Holes” Carr et al. (2021)

Limits on “heavy” PBH (and MACHO) abundances



Source: A Brief Review on Primordial Black Holes