

Astrophysics of Dark Atoms

Workshop on Atomic Dark matter

University of Pittsburgh 01/28/2022

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Elevator Pitch

a.k.a why dark disk typically does not form in the Milky Way

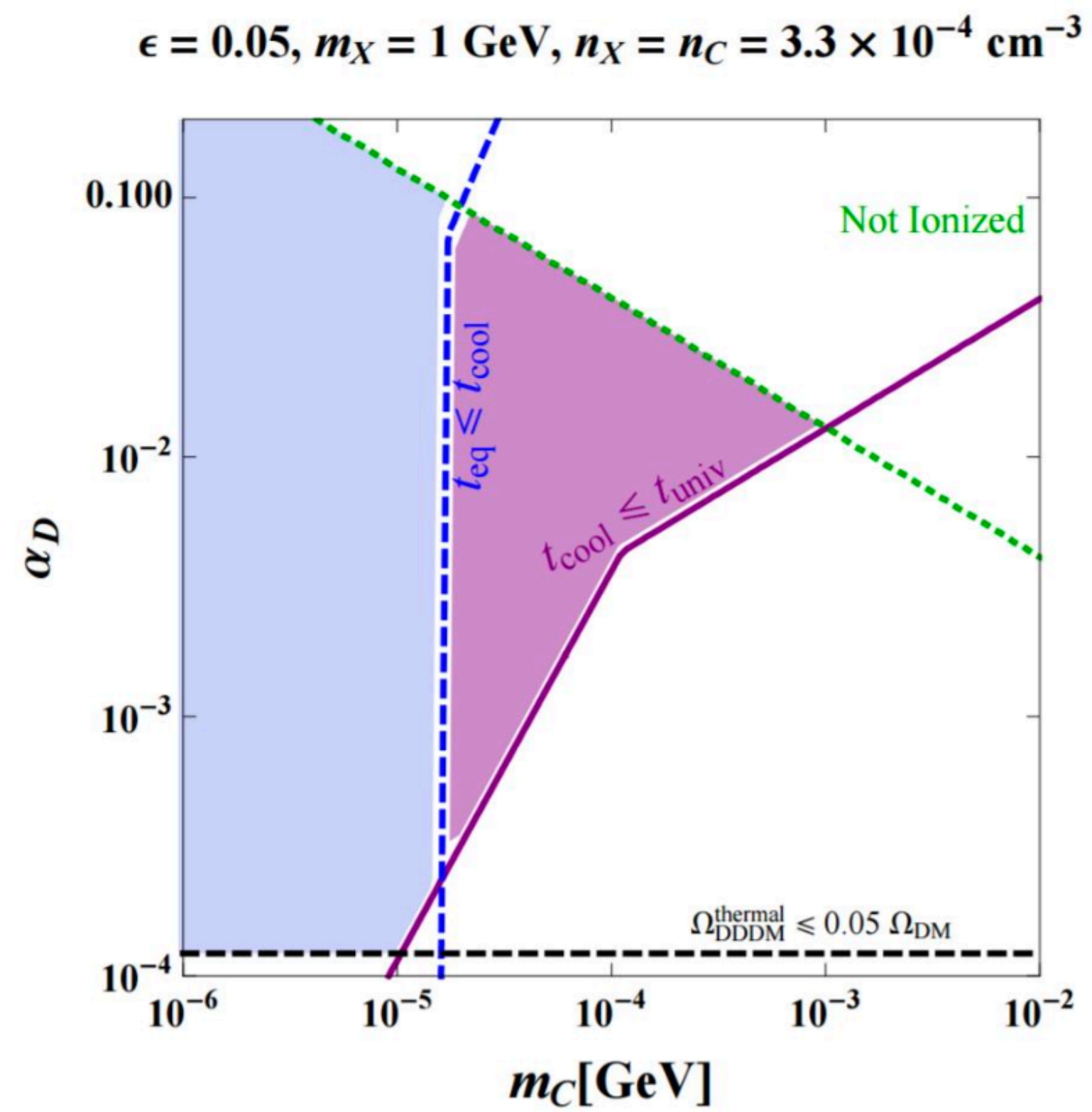
- Atomic Dark Matter with no nuclear physics (no feedback)
- Cools efficiently early in the universe in small halos forming a disk
- Disk further fragments to dark clumps (“stars”)
- Disk does not survive subsequent major mergers
- No SN feedback to return the gas back to the halo, no further disk formation possible
- Hydro simulations will map to “ground truth”

Dark Atoms

Introduction

- Fraction ϵ of dark matter can be atomic in nature
- Dark Proton (m_X), dark electron ($m_c \ll m_X$)
- Dark photon with coupling (α_X) and temperature $\xi = \frac{T_{\gamma'}}$
 T_{CMB}
- Crucial assumption: NO nuclear physics in the dark sector
- Motivated by solutions to naturalness (Twin Higgs, N-Naturalness etc.)

Motivation



Fan et. al. 2013



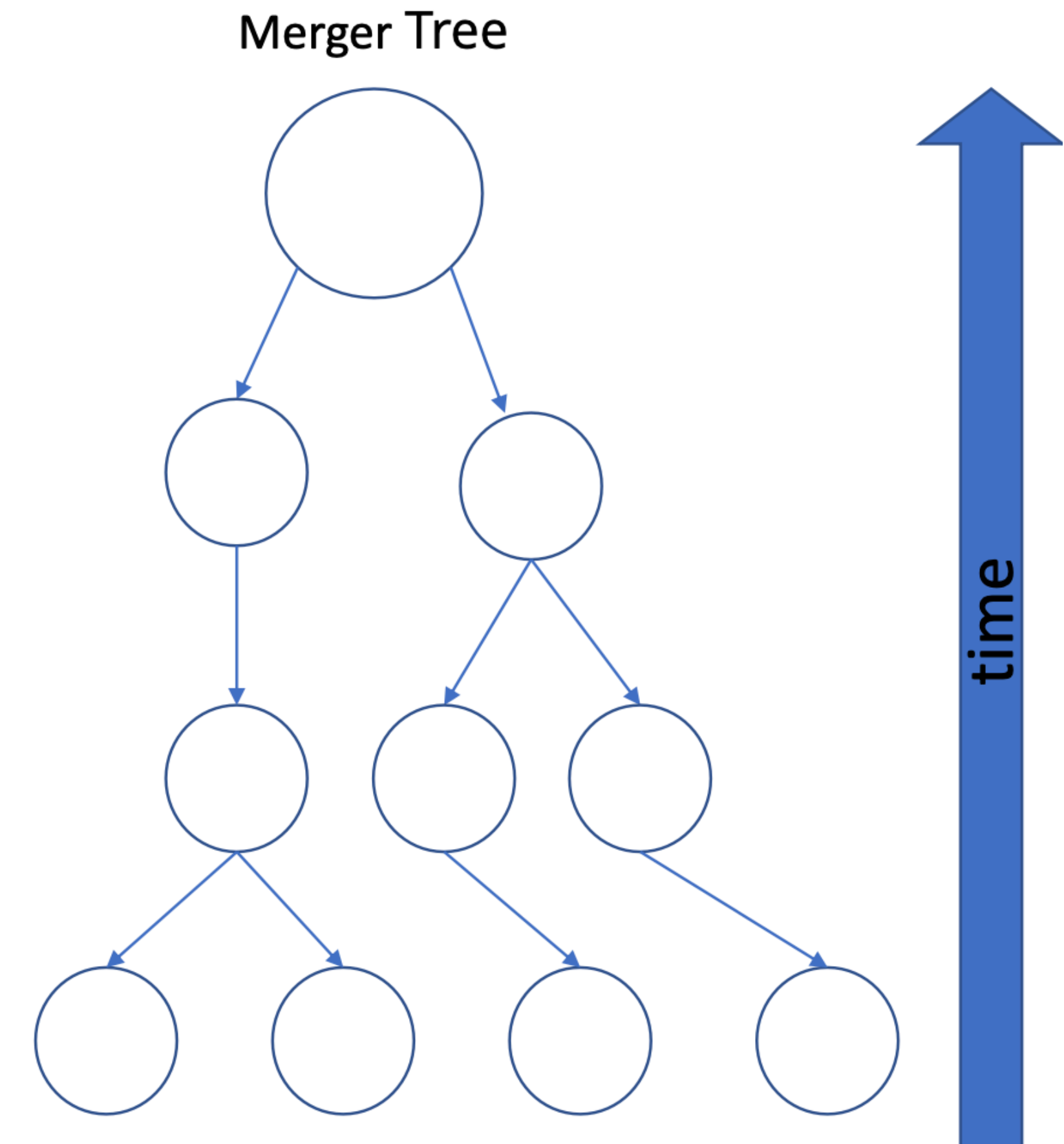
SMBC comics

Dark Atoms Parameter Space

- $1 \leq m_X \leq 10 \text{ GeV}$
- $m_c \in [10^{-5} \text{ GeV}, 10^{-2} \text{ GeV}]$
- $\alpha_X \in [10^{-3}, 10^{-1}]$
- $\xi = \frac{T_{\gamma'}}{T_{CMB}} = 0.5$ (results relatively insensitive)

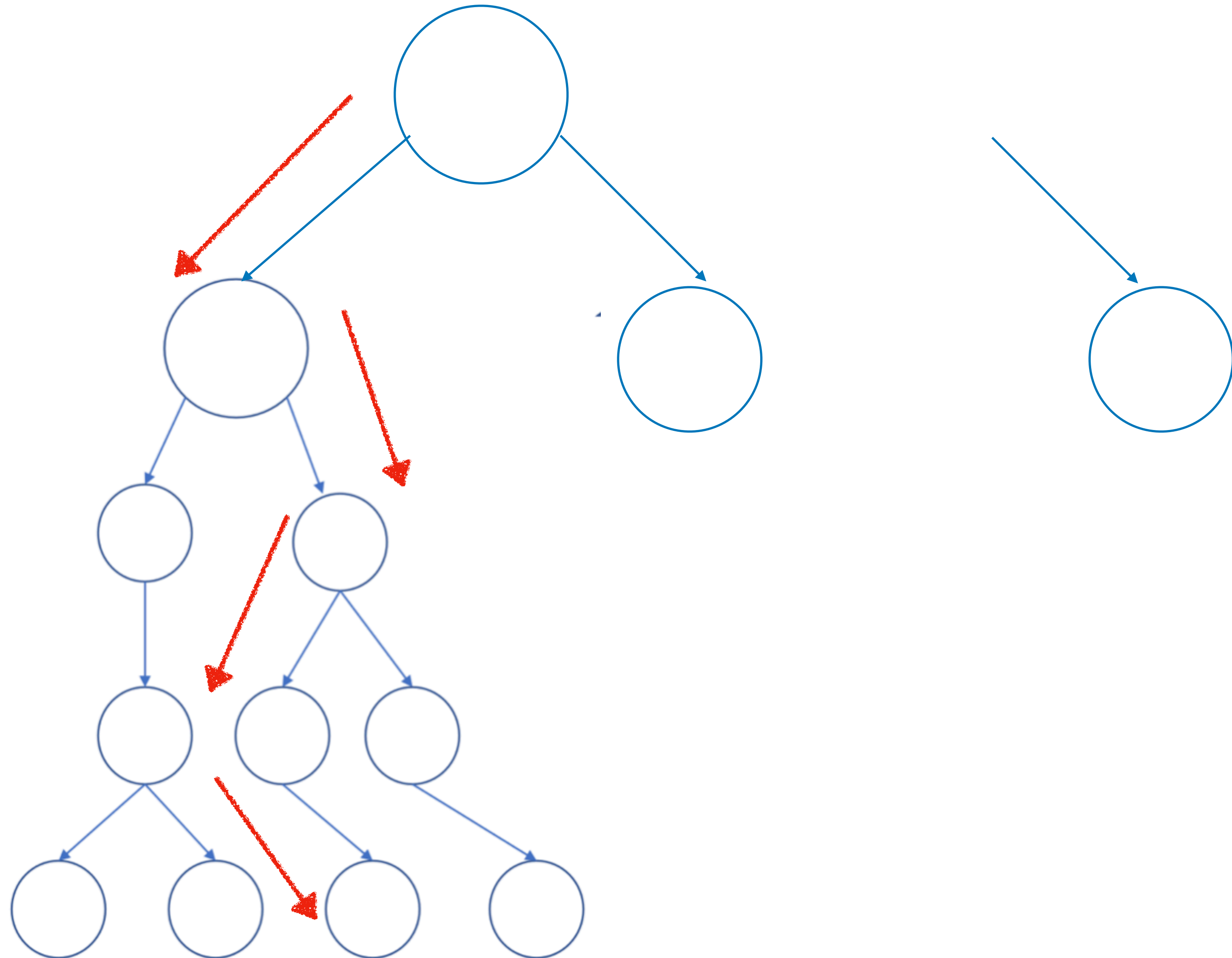
Merger Trees

- PS formalism gives Halo mass function
- Dictates the probability of split and daughter mass
- Iteratively generate a merger tree
- Technical:
 - $M_{res} = 3 \times 10^7$
 - $z_f = 10$
- See Lacey and Cole (1993,2000)

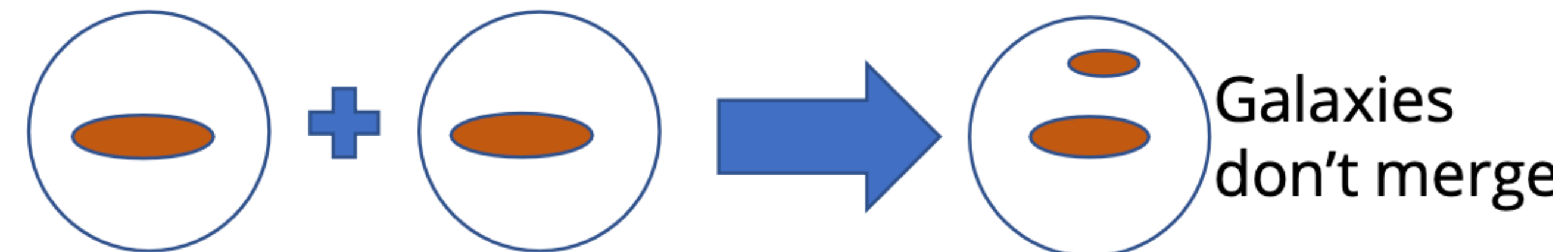
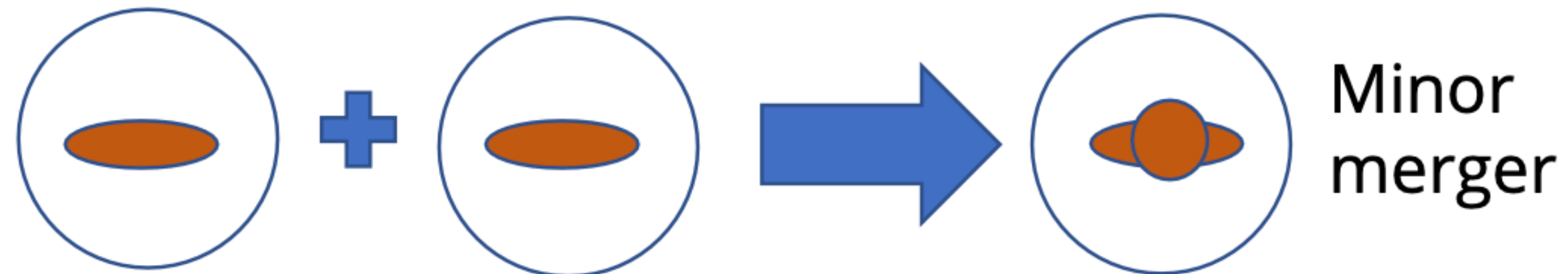
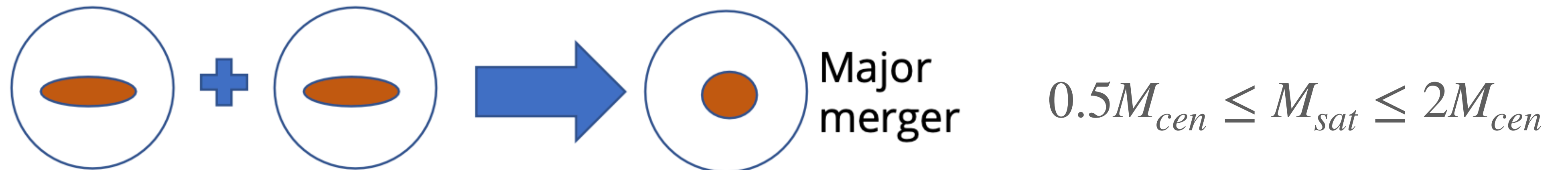


Merger Tree - “Halo Formation”

t_{halo}



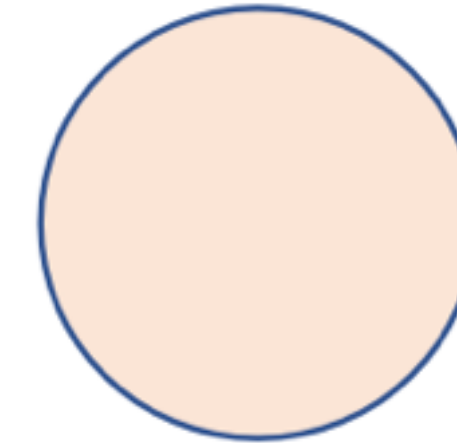
Merger Tree - Galaxy Formation



$$t_{mrg} < t_{halo}$$

Galaxy - 4 extremes of Dark Milky Way

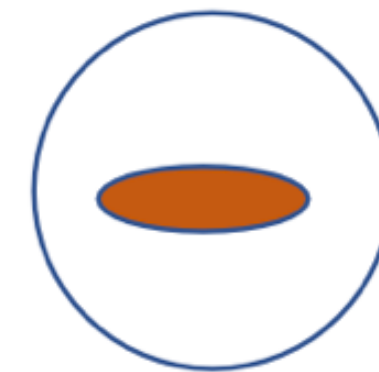
- No cooling - None of the gas is able to cool



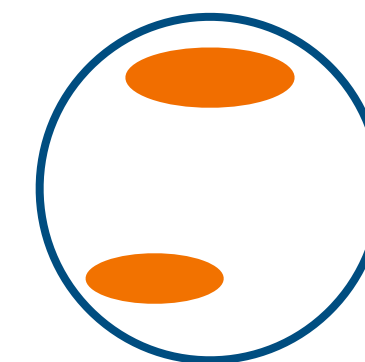
- Dark Bulge - Disks destroyed by major mergers



- Dark disk - Disk survives mergers



- Dark Halo - Galaxies form in satellite halos

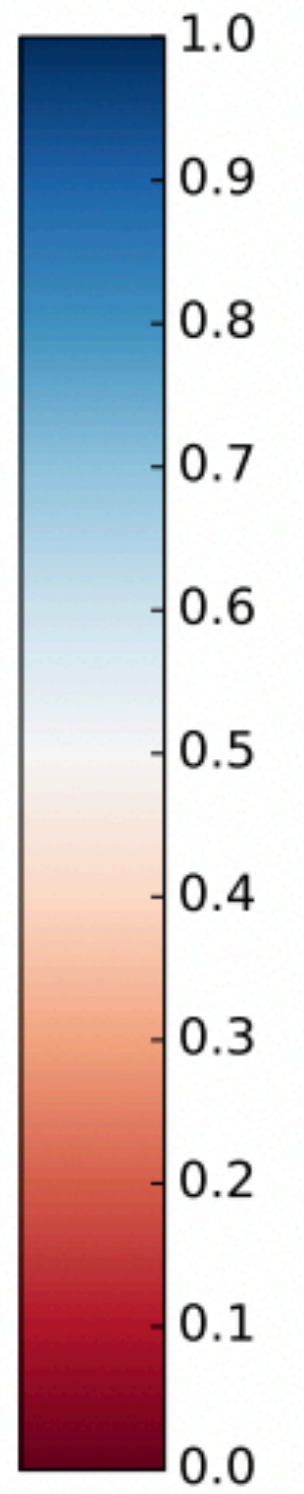
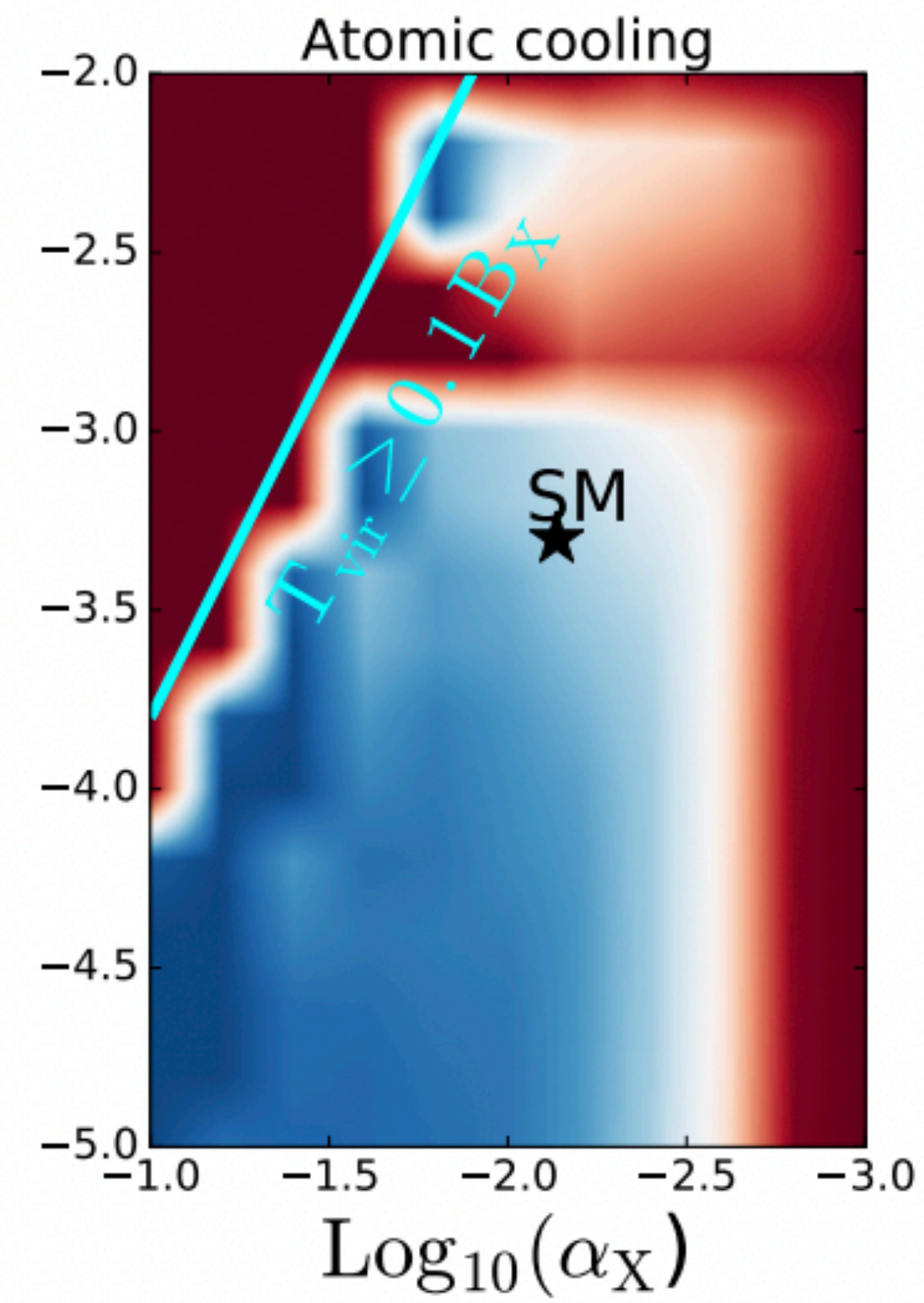
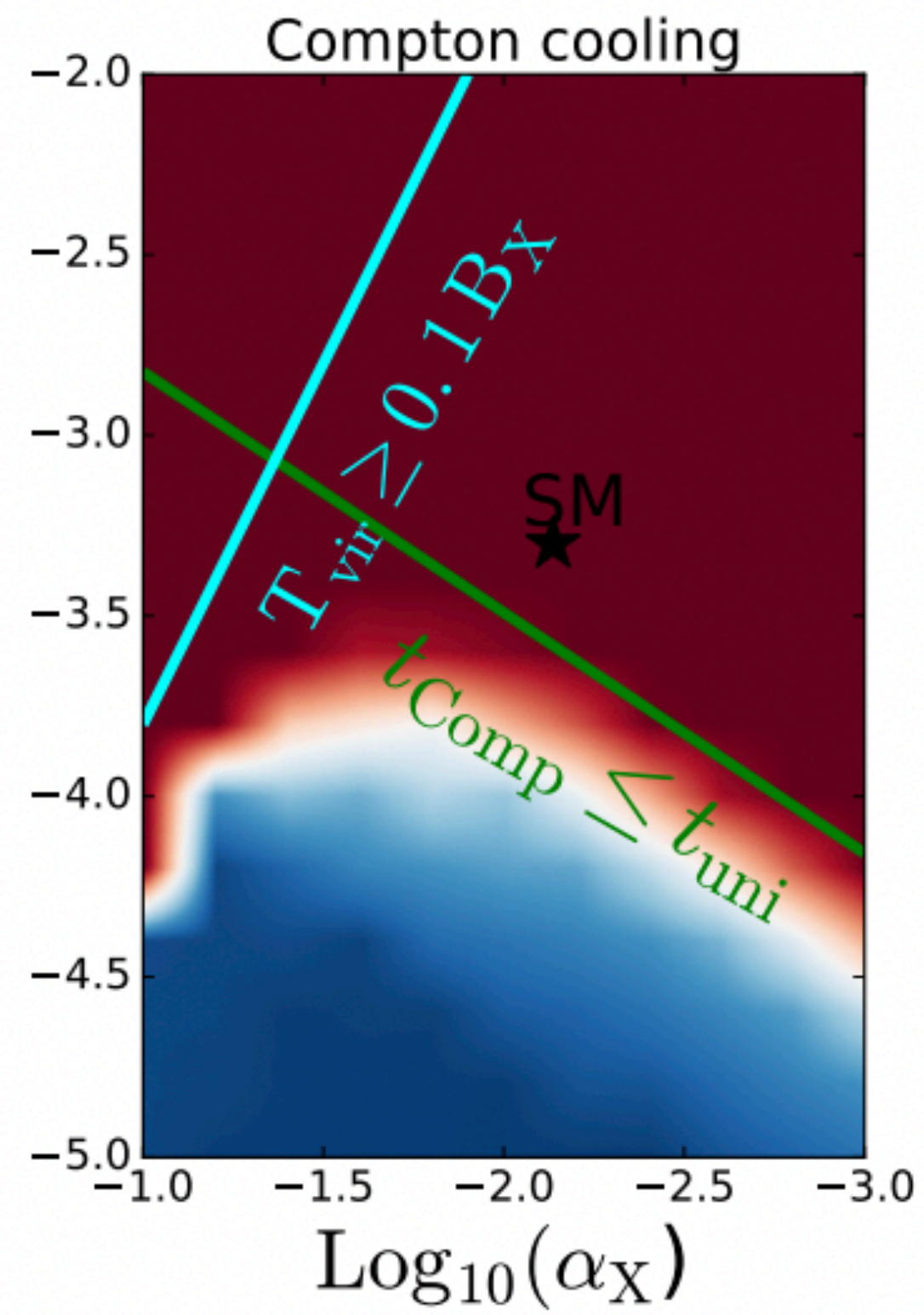
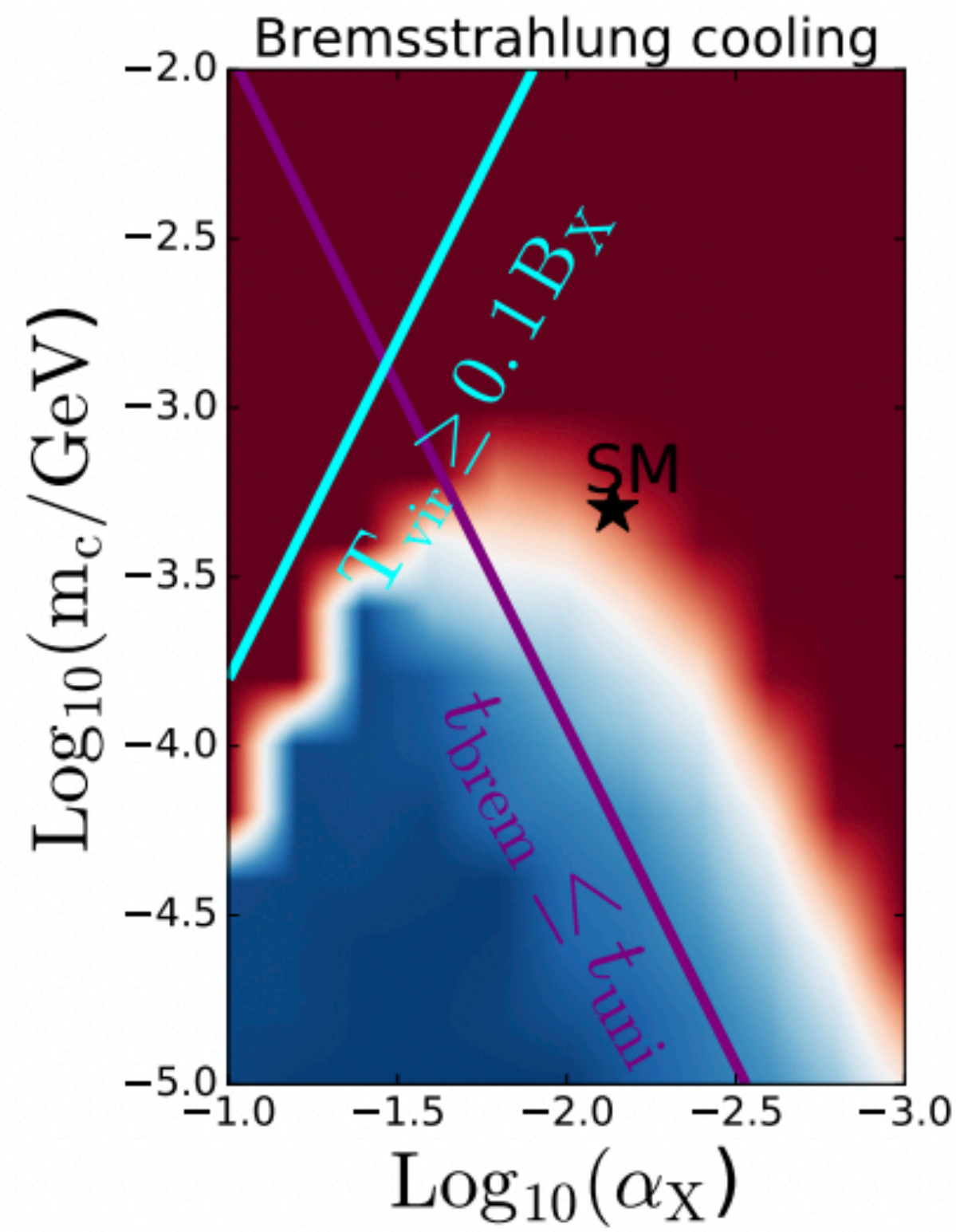


Timescales

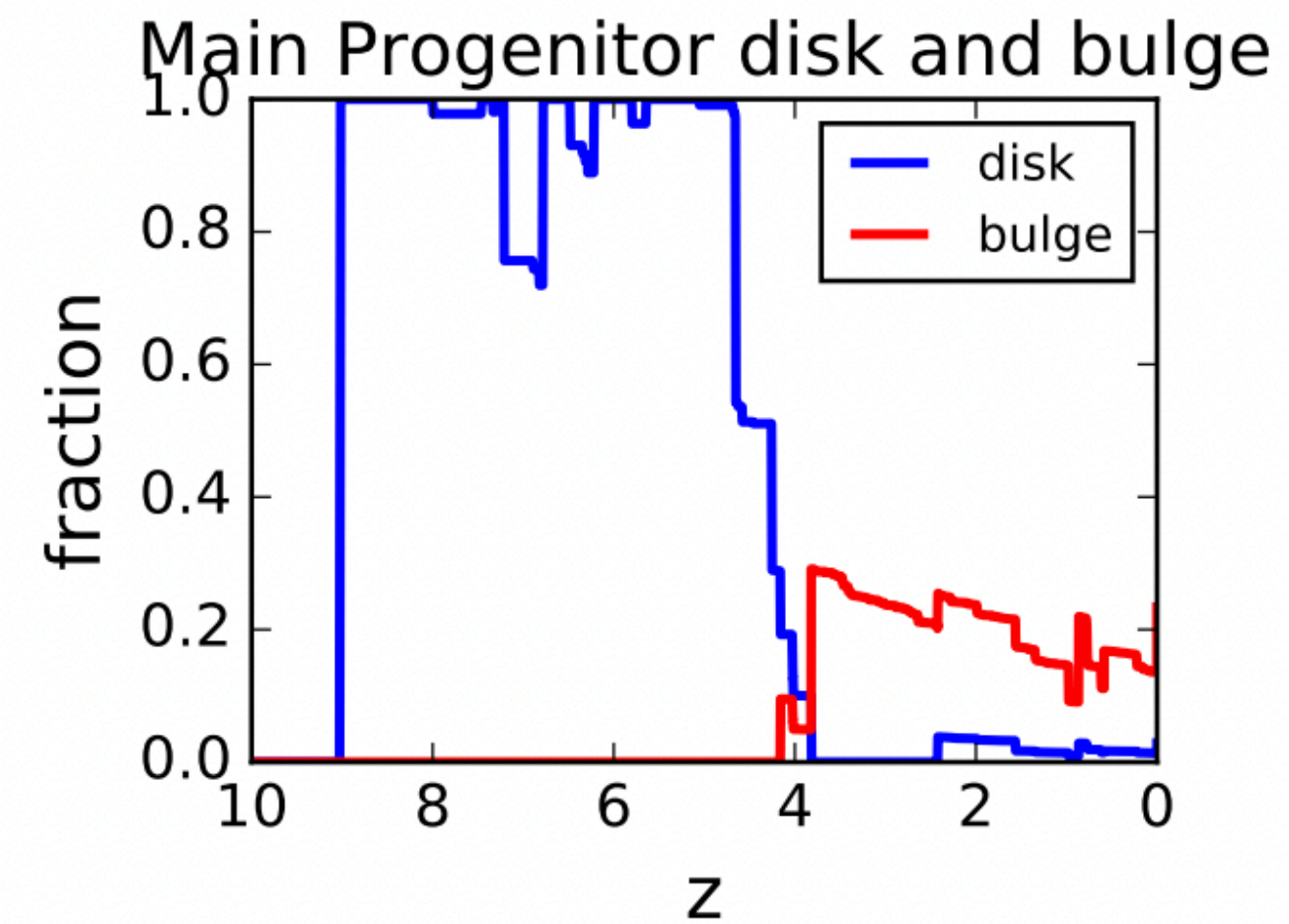
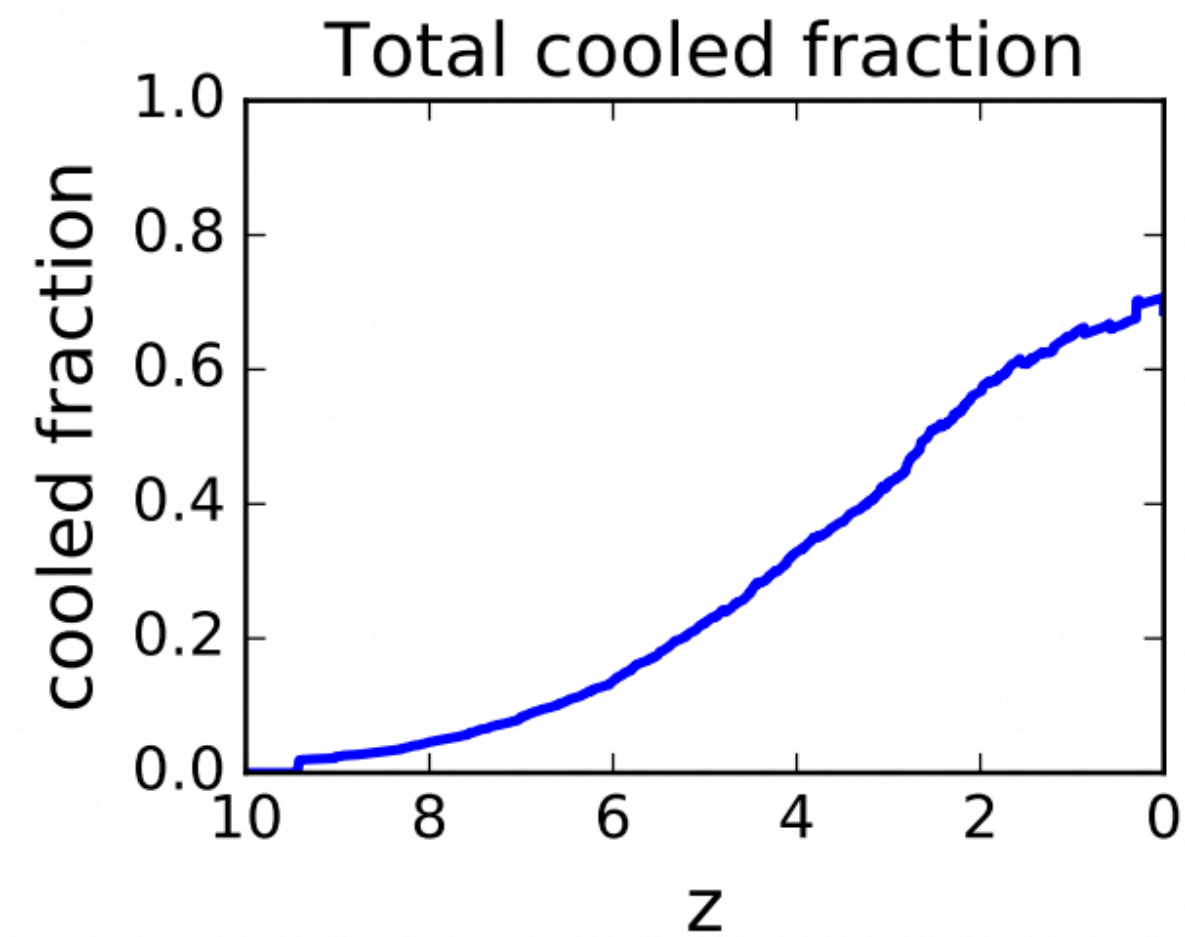
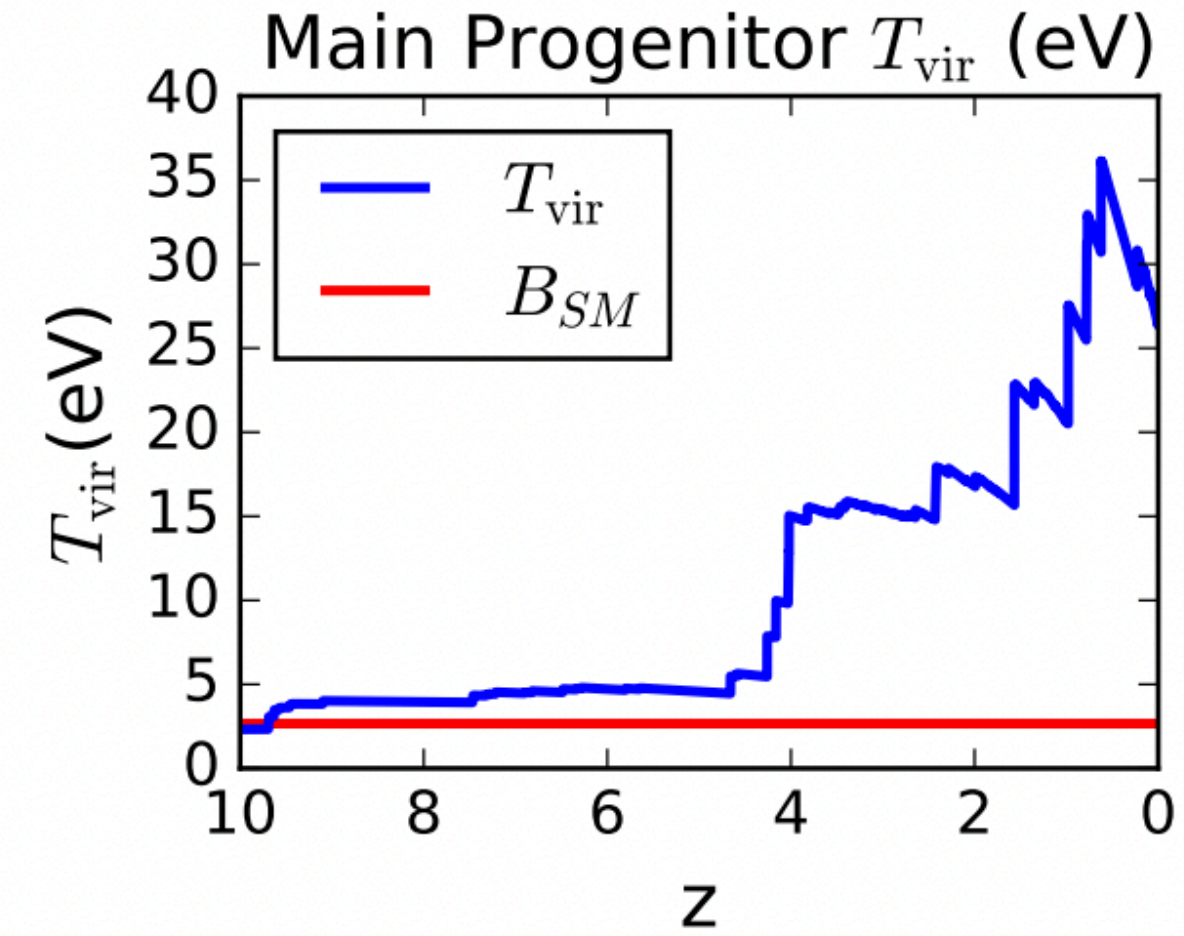
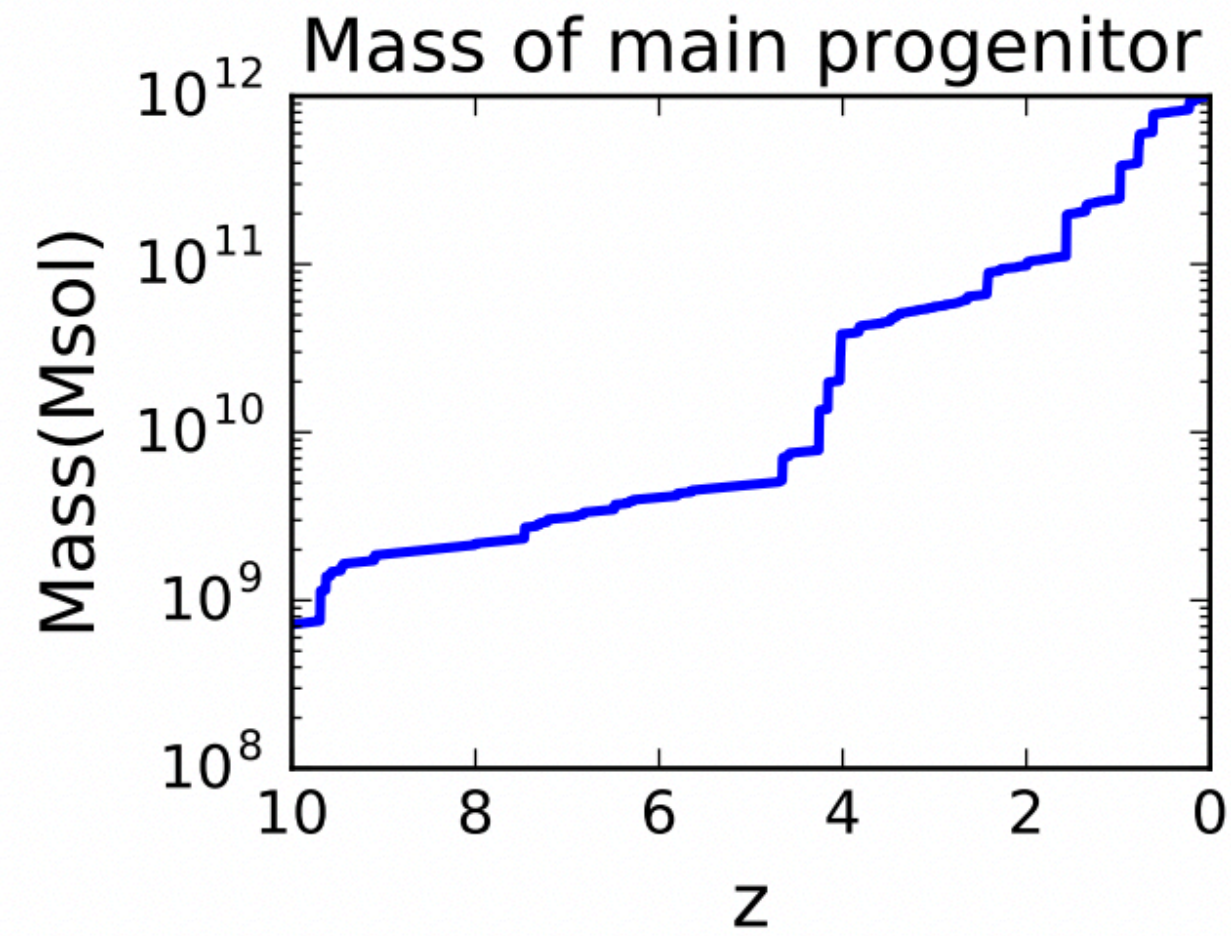
- Cooling - Atomic, Brehmsstrahlung, Compton
- Equilibration - equilibrating protons and electrons
- Dynamical time - Time to virialize
- For gas in halo to cool need

$$[t_{cool}, t_{dyn}, t_{equil}] < t_{halo}$$

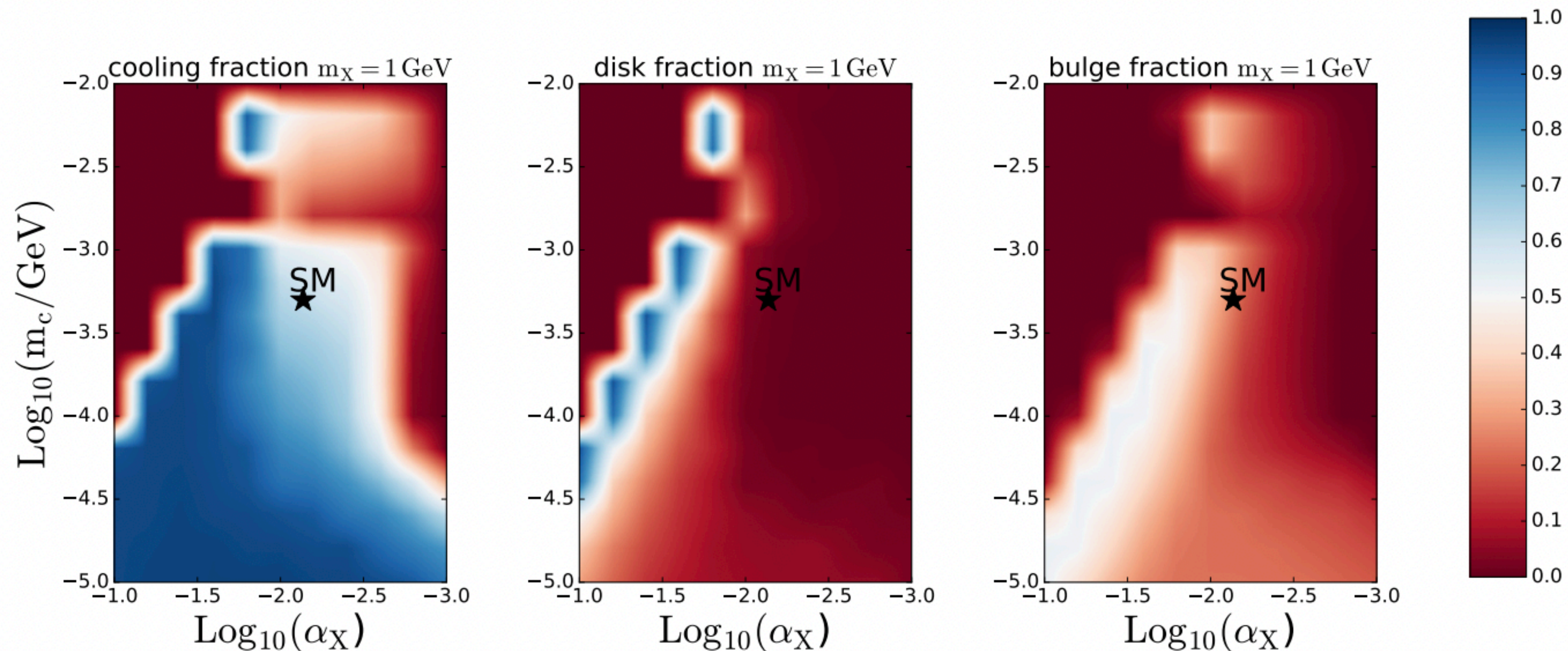
ABC Coolings



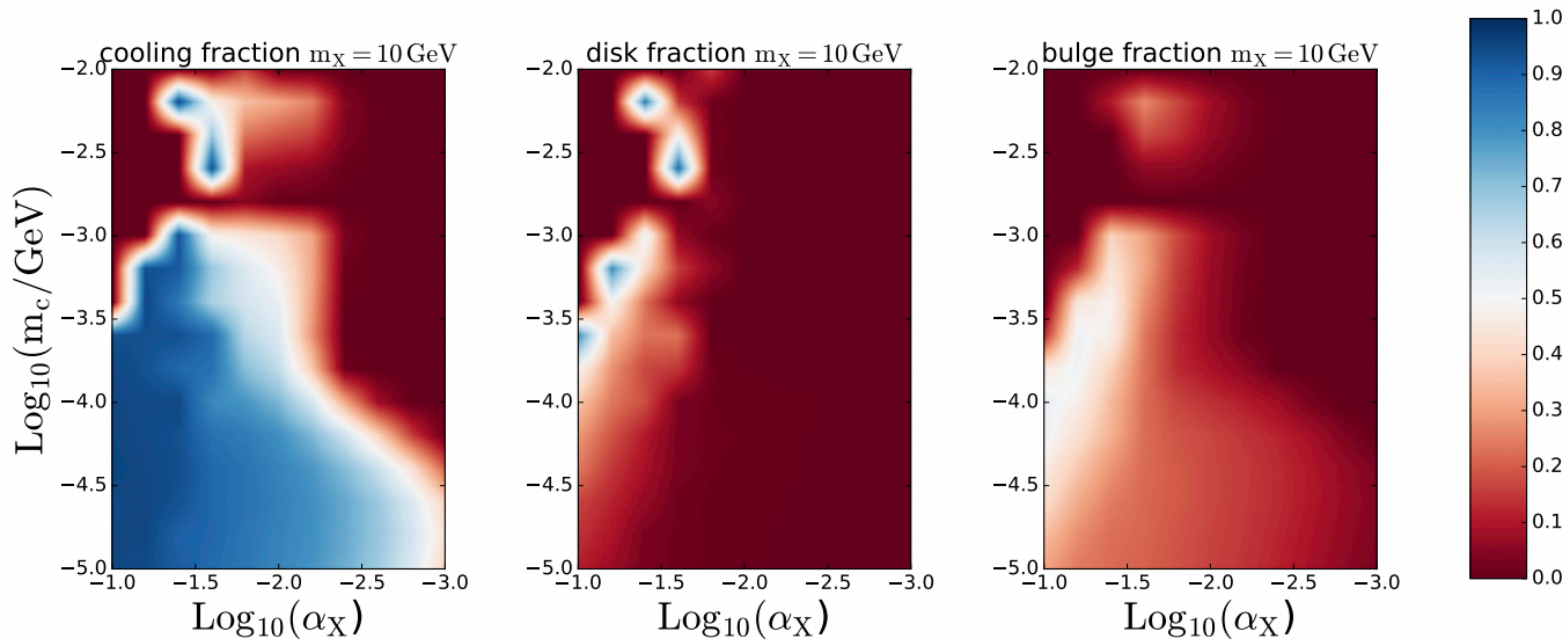
Dark Galaxy, SM parameters



Results



Results



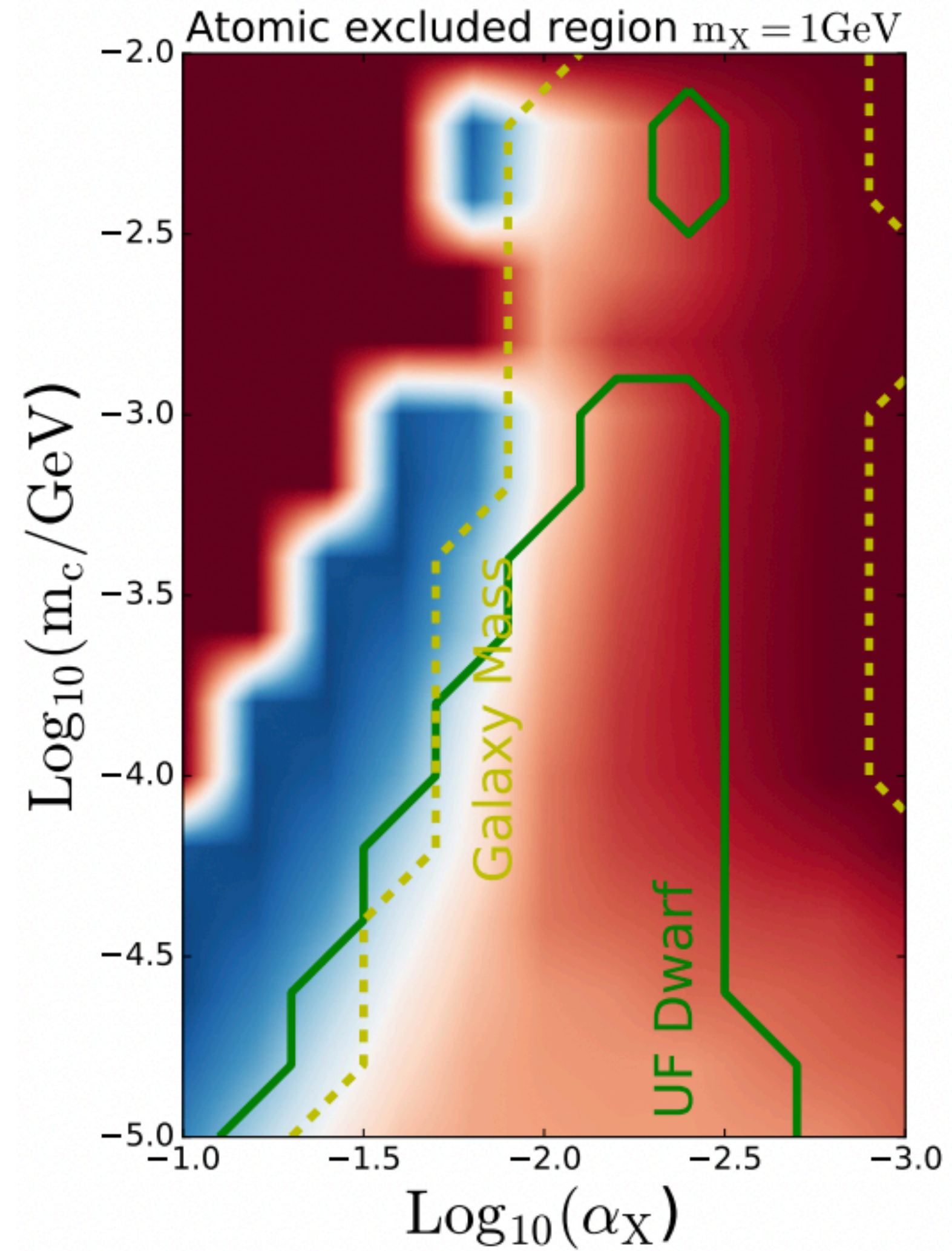
Constraints

Mass of central region of galaxy

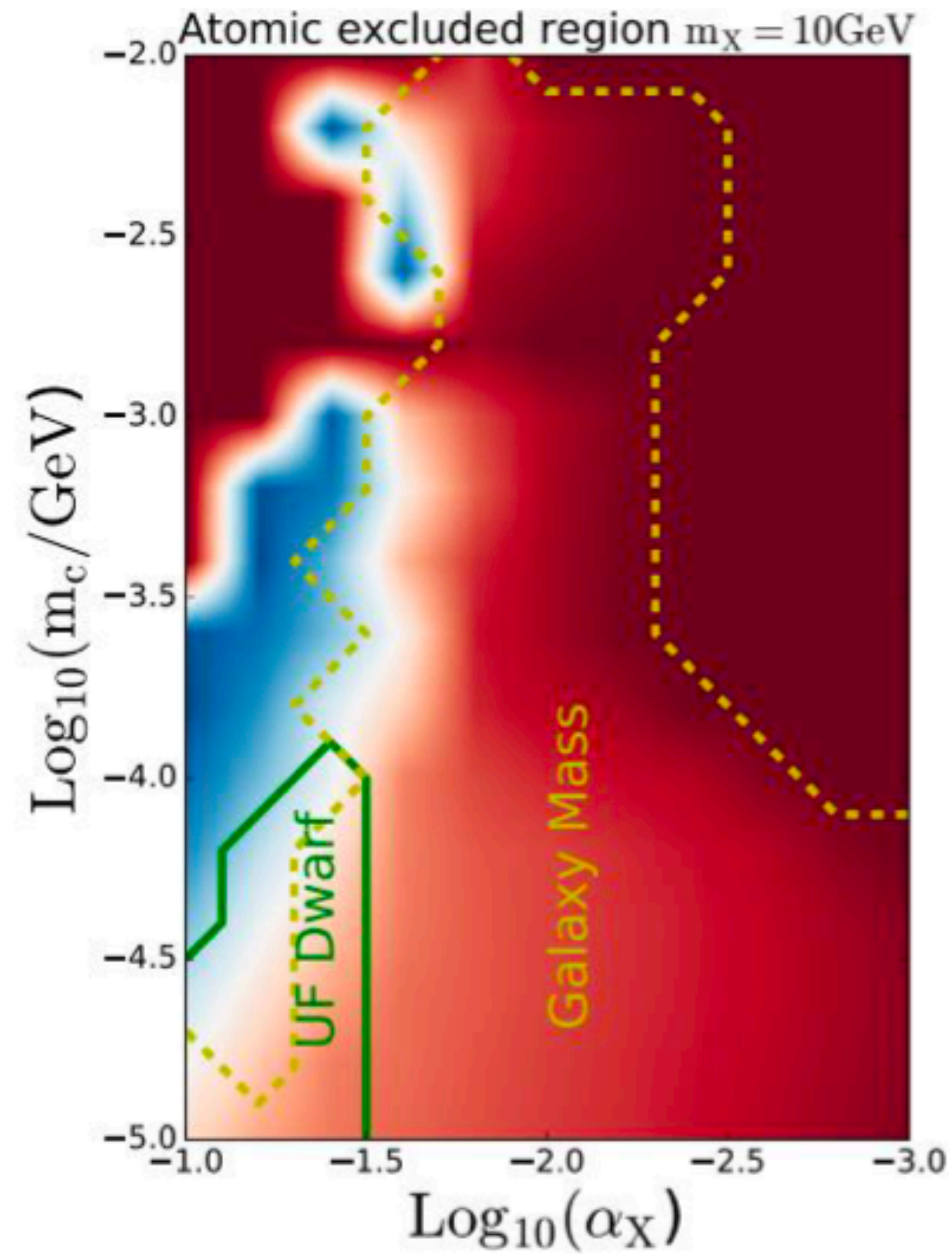
- Mass to light ratio - Estimates mass of stars unto factor of two
- Compare to mass from rotation curves or strong lensing (CDM negligible)
- Only 2% of baryons end up in stars

$$\epsilon \times \left\{ f_{\text{bulge}} \left(\frac{r_{\text{MW}}}{r_{\text{s}}} \Big|_{\text{bulge}} \right)^3 + f_{\text{disk}} \left(\frac{r_{\text{MW}}}{r_{\text{s}}} \Big|_{\text{disk}} \right)^2 \right\} \lesssim 0.02$$

Constraints



Constraint



Conclusions

- Merger Tree provides a systematic way to form atomic dark matter galaxy
- “Quick” to run simulations and explore a large parameter space
- Most of the atomic dark matter parameter space forms a bulge galaxy or a dark halo
- $< 10\%$ of the parameter space forms a dark disk

Conclusions

- Existence of a bulge ruled out by milky way stellar mass measurement if ADM is 5%
- Fractions order of magnitude smaller probably also mostly ruled out in the same region
- Strongest constraints so far on ADM parameter space
- Based purely on morphology, no jeans mass, BH formation etc. needed

Wishlist

- Compare and calibrate to “ground truth” - Hydro simulations
- Incorporate molecular cooling
- Incorporate accurate Jeans mass calculation
- Incorporate possible feedback from dark stars
- Use results to constrain (or discover!) existing parameter space through Gaia, LIGO etc.

Questions?