AXION STARS:

MASS FUNCTIONS AND CONSTRAINTS

Based on arXiv:2406.09499
with Patrick J. Fox and Huangyu Xiao

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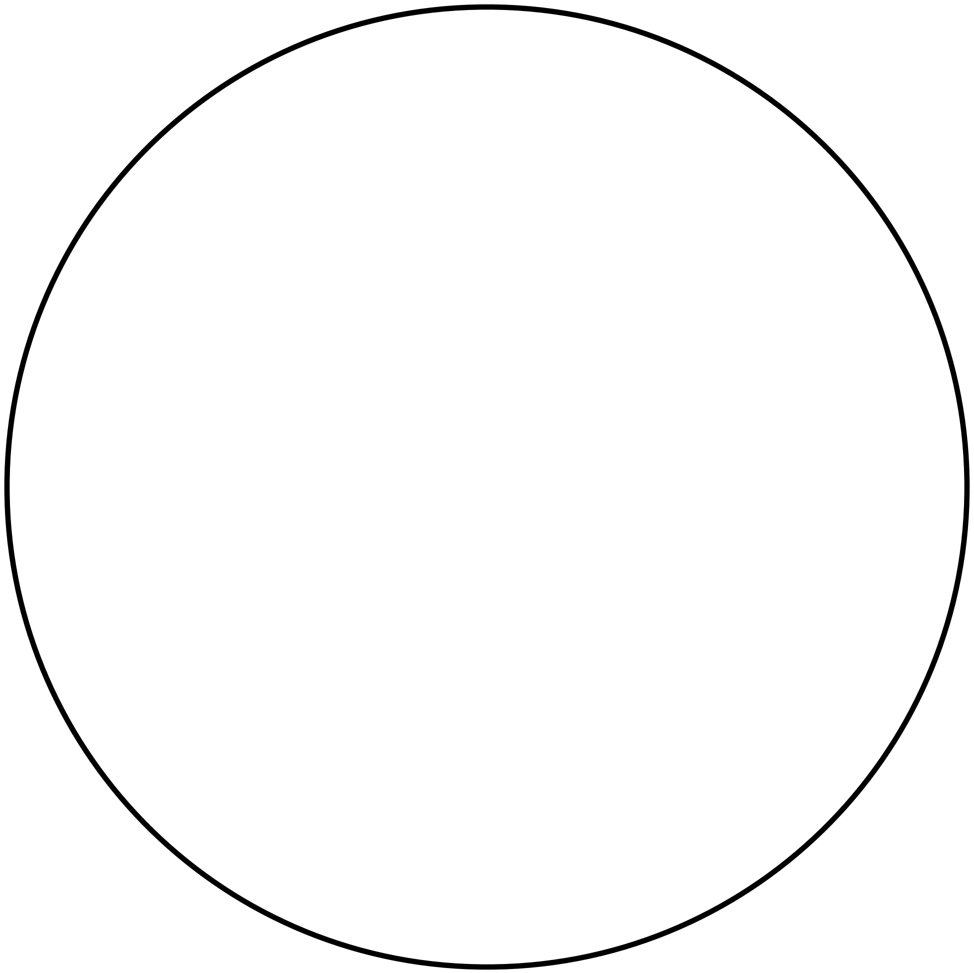
08/28/2024 TeVPA 2024

How are normal stars formed?



- CDM halo with $\delta \gg 1$ deep in matter-domination

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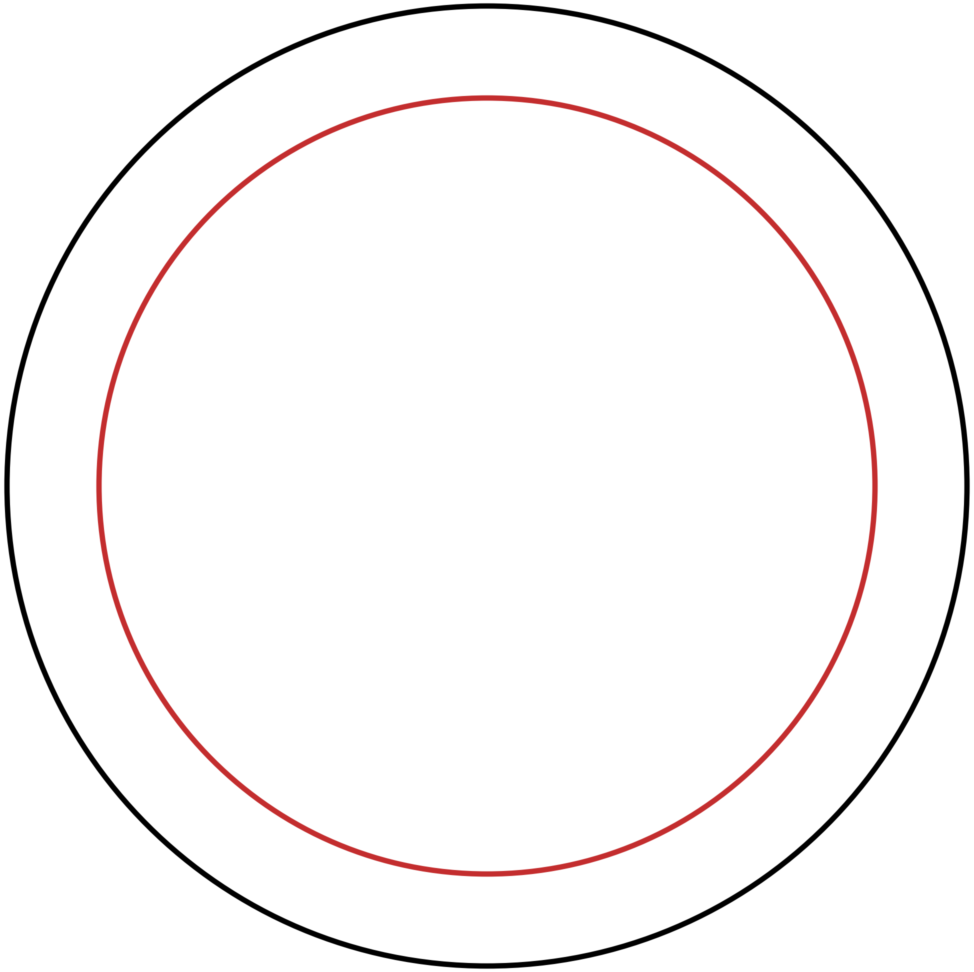

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- Baryons fall into the CDM potential well

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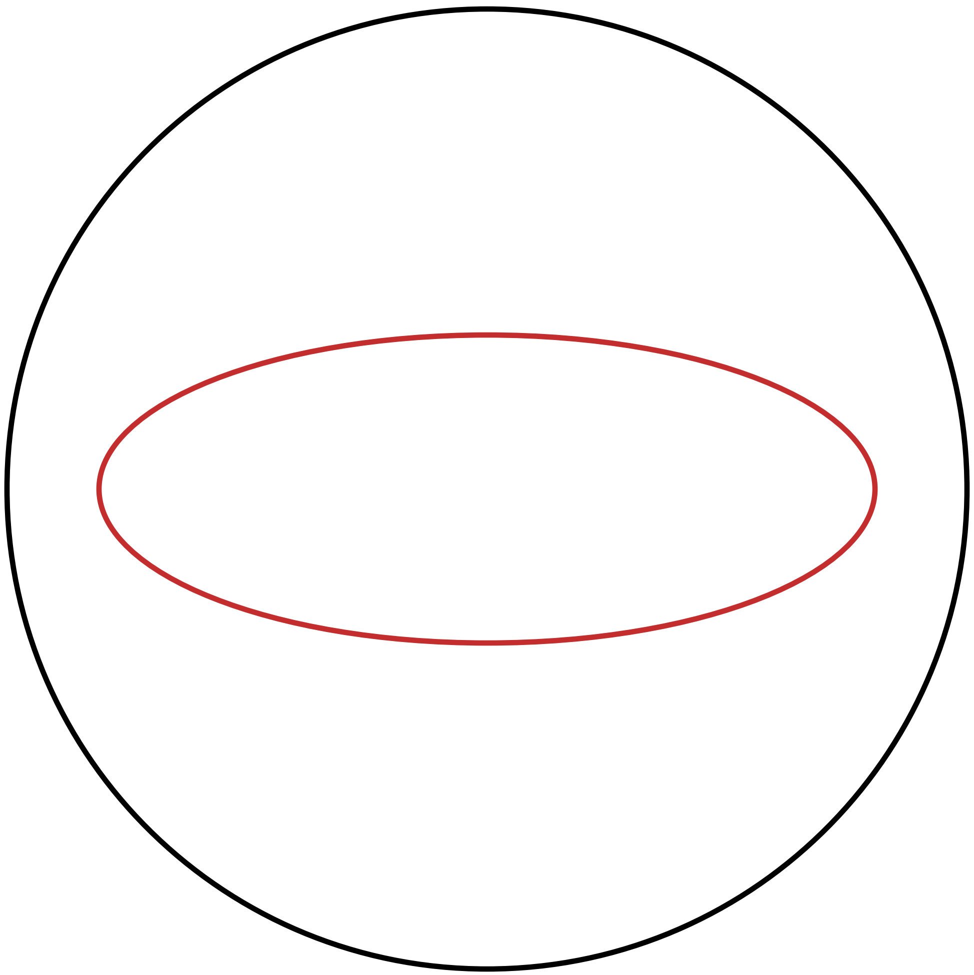

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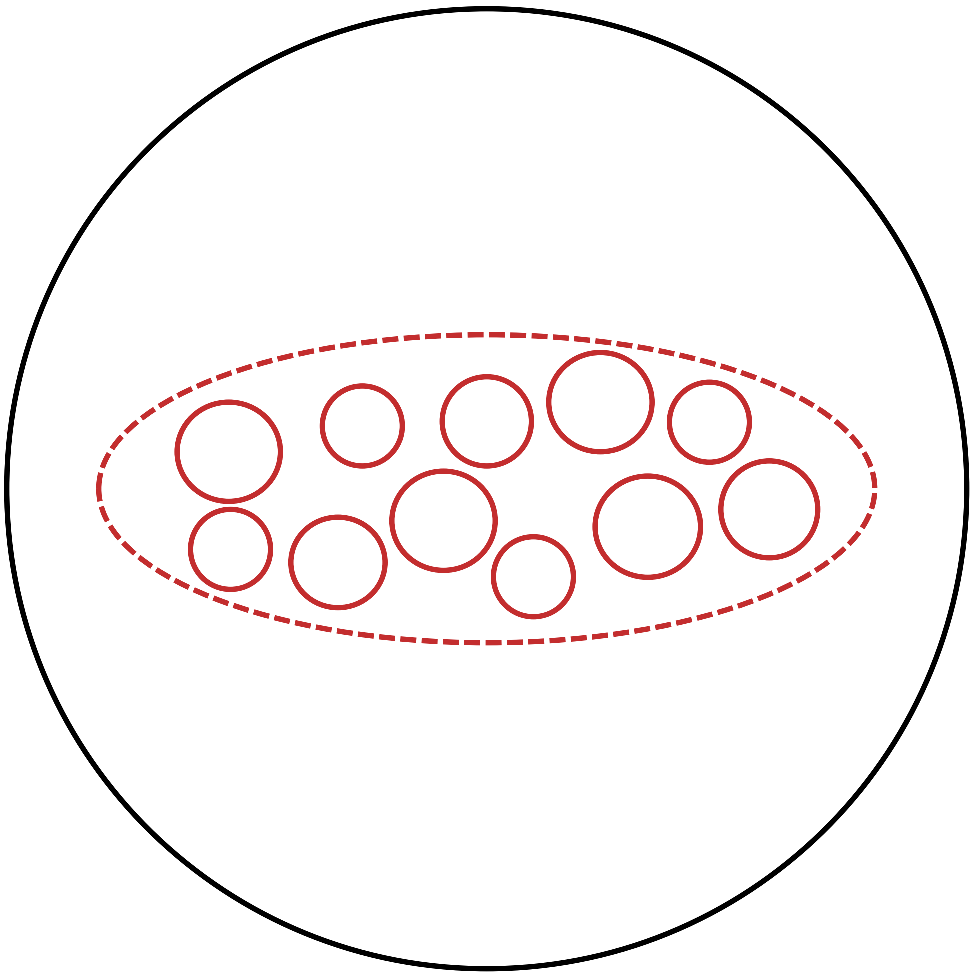

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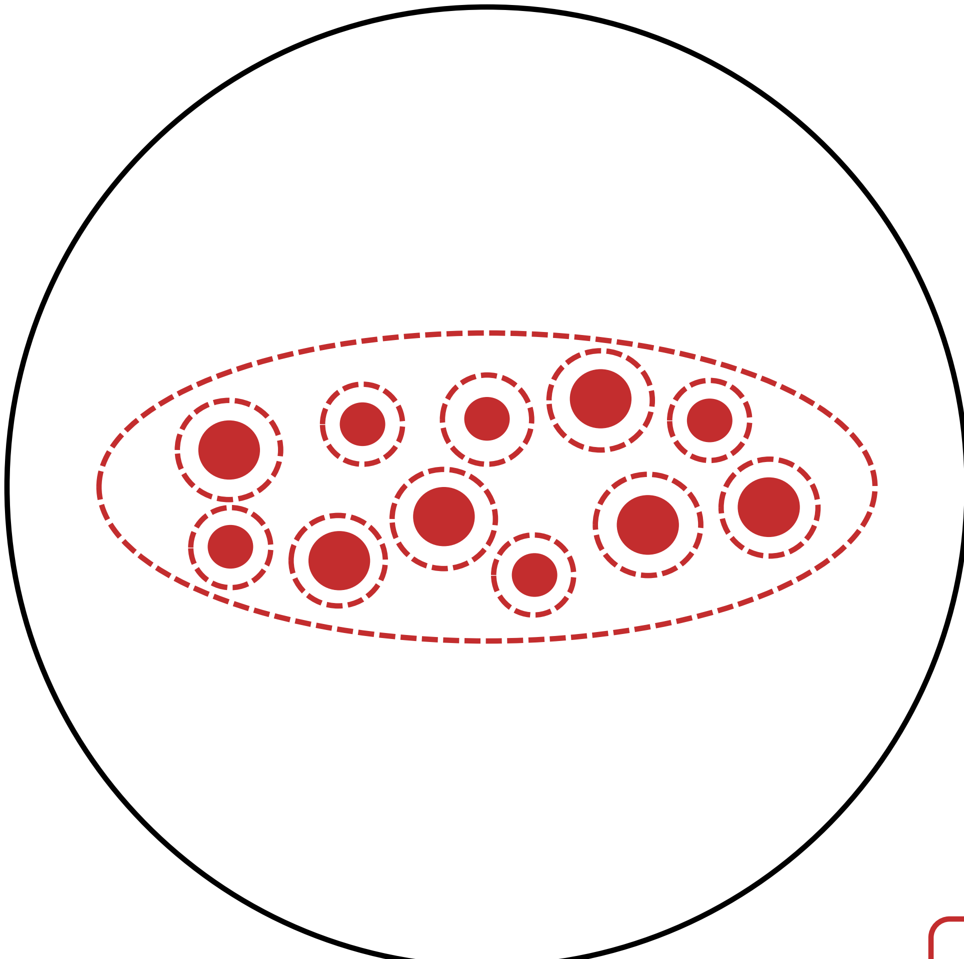

- CDM halo with $\delta \gg 1$ deep in matter-domination
- Baryons fall into the CDM potential well
- They collapse into a disk due to interactions and their angular momentum
- Fragments due to rapid cooling
- Each blob forms a stable compact object

Need interactions, especially cooling

For dark star formation from fragmentation, see 1812.07000 and Melissa's talk

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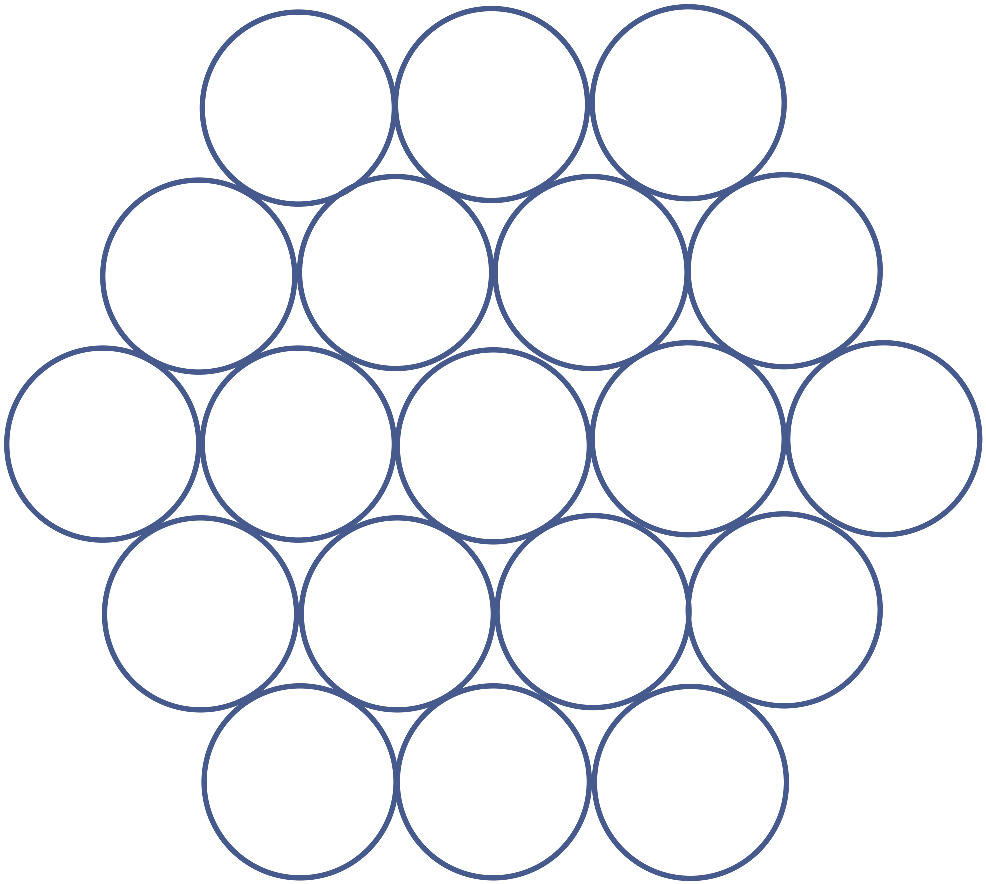

- Different Hubble patches after inflation

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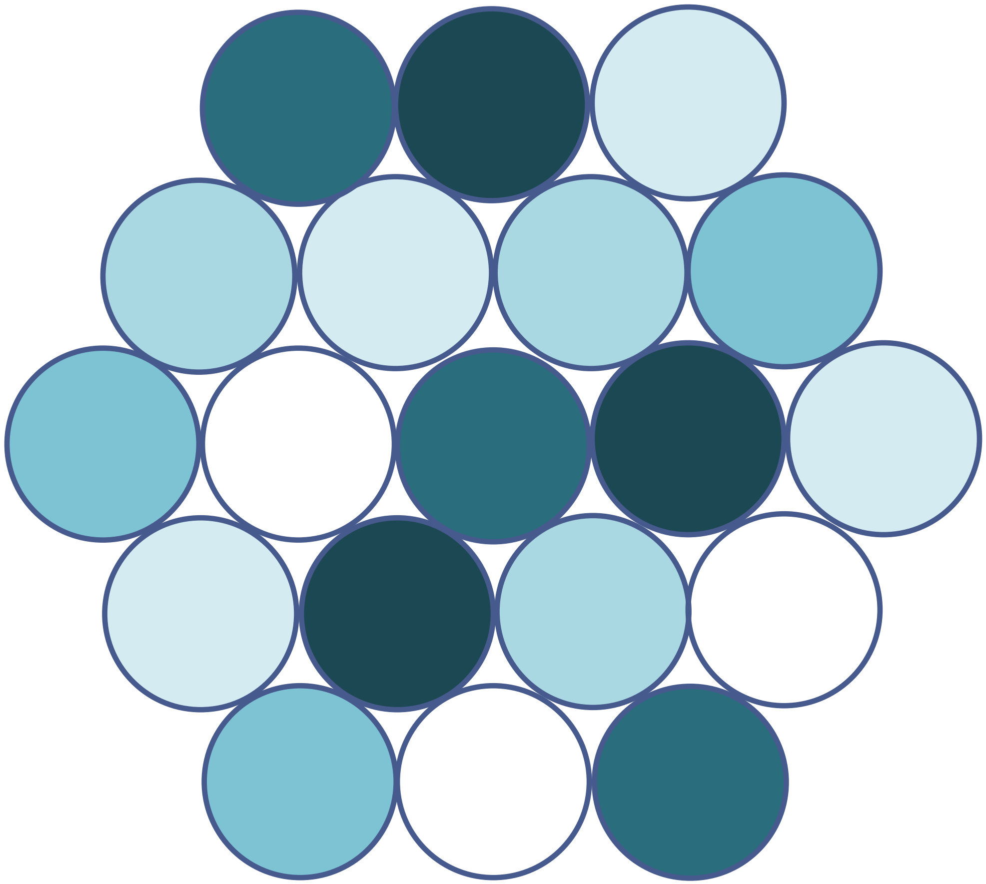
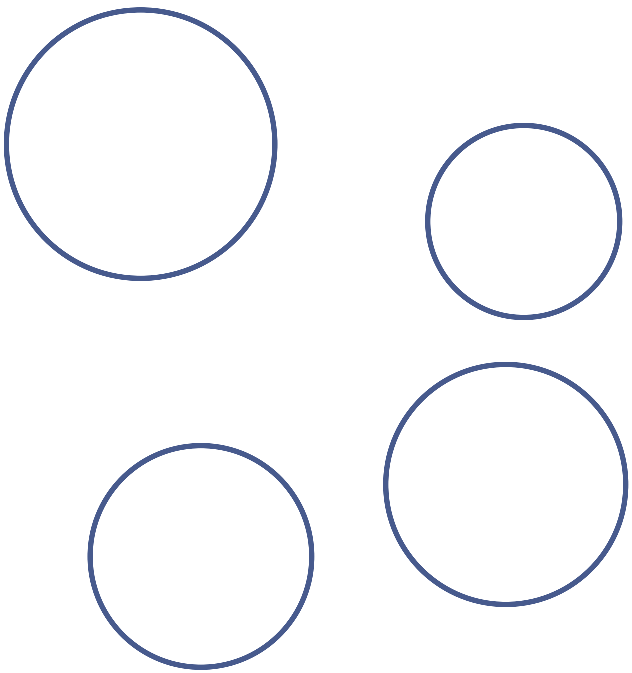


- Different Hubble patches after inflation
- If PQ symmetry is broken after inflation, Hubble patches pick different initial values

$$\theta \in (-\pi, \pi)$$

- Axions can have large perturbations at small scales in the early Universe
- Yields a white-noise power spectrum

Axion minihalos



- Axion minihalo (minicluster) forms from the large perturbations early times

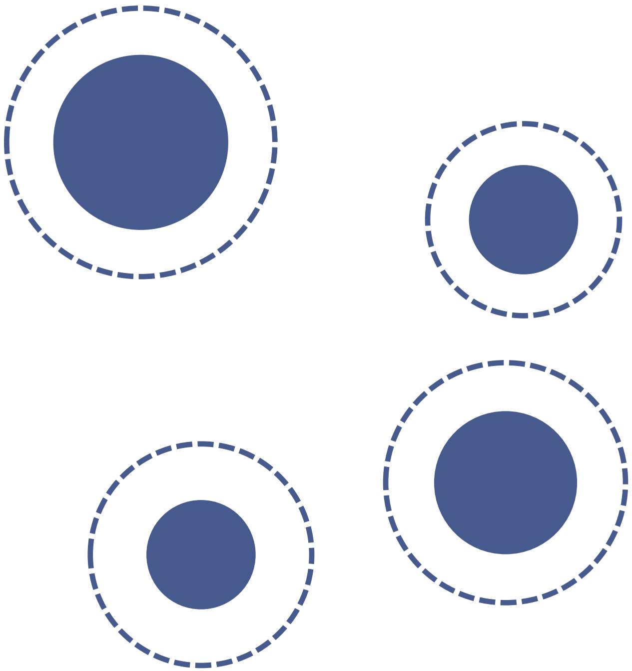
- Such minihalos are already light:

$$M_{h,c} \sim 10^{-14}\, M_{\odot} \left(\frac{\mu\mathrm{eV}}{m_a}\right)^{0.51}$$

for QCD axions

- Mass distribution of minihalos can be obtained from the Press-Schechter formalism

Axion stars



- Stable configuration of axion fields

$$E_\star = -\frac{GM_\star^2}{R_\star} + c_1 \frac{M_\star}{2m_a^2 R_\star^2}$$

Visinelli et al, 1710.08910

- Form and grow after one relaxation time

$$\tau_{\rm gr} \sim \left(f_{BE} n \sigma_{\rm gr} v\right)^{-1}$$

Levkov et al, 1804.05857

Gravitational interaction is enough

- The mass of axion star is determined by m_a, M_h, and t

Goal of this work

- Getting the mass function of axion stars needs heavy numerical simulations, especially the contribution from axion strings

- We propose a reasonable way to calculate the mass function analytically with the white-noise part

- We also provide constraints on axion masses from the mass function

We consider two axion models

- QCD axion
  - Solves the strong CP problem
  - $m_a(T) \sim m_a(0) \left(\frac{\Lambda_{\mathrm{QCD}}}{T}\right)^4$ for $T > \Lambda_{\mathrm{QCD}}$
  - Besides this, we can still ignore the interactions other than gravity

- ALP (Axion-like particle)
  - We ignore all the interactions
  - The mass of axions does not depend on the temperature
  - Starts to oscillate at its zero-temperature mass

To get the axion star mass analytically

- We consider axion minihalos at matter-radiation equality and let axion stars evolve inside minihalos for one Hubble time

- Matter-radiation equality because $t_J \sim t_{eq}$

- One Hubble time because merger of minihalos increase the relaxation time and axion star formation ceases

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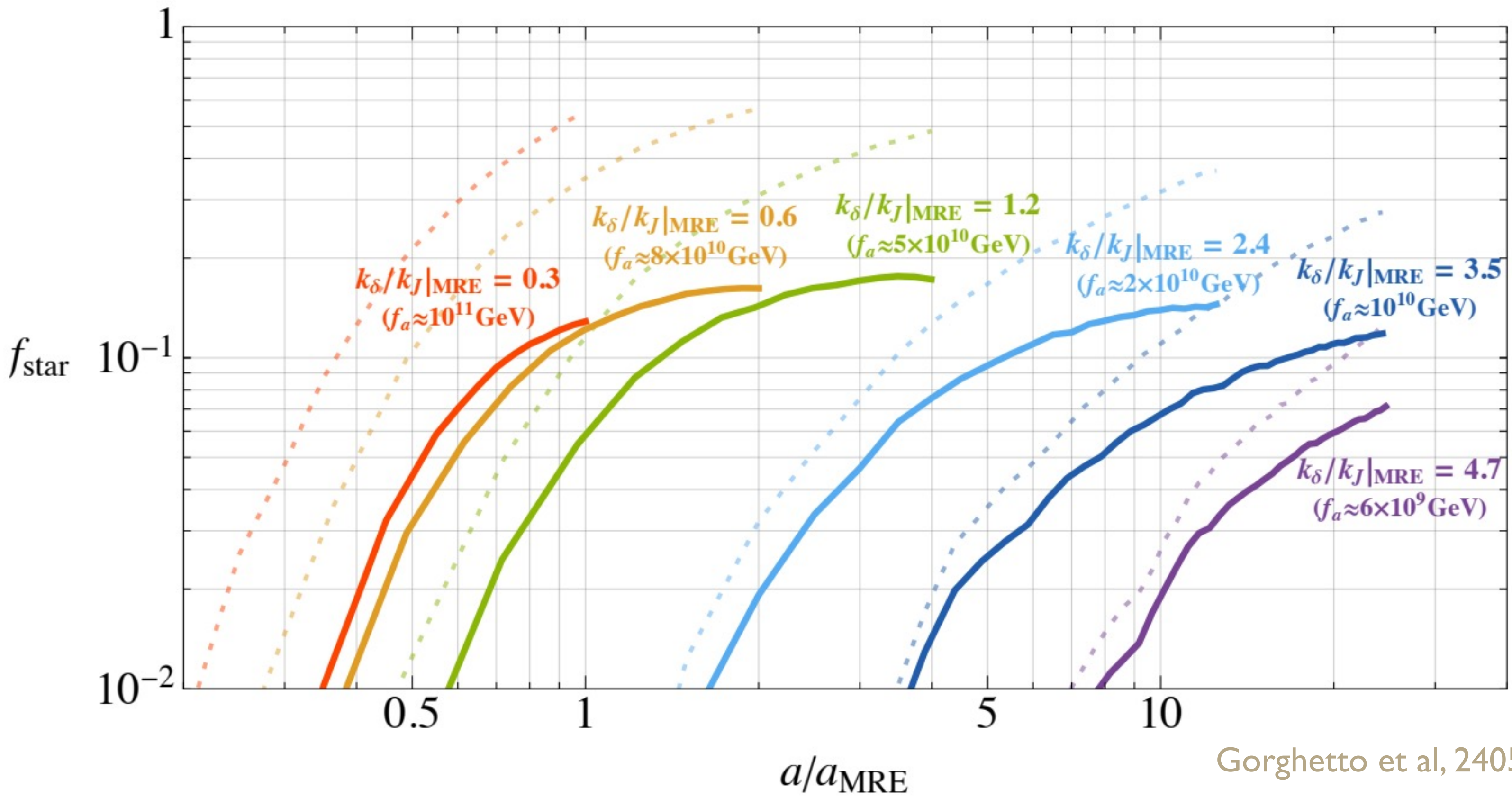
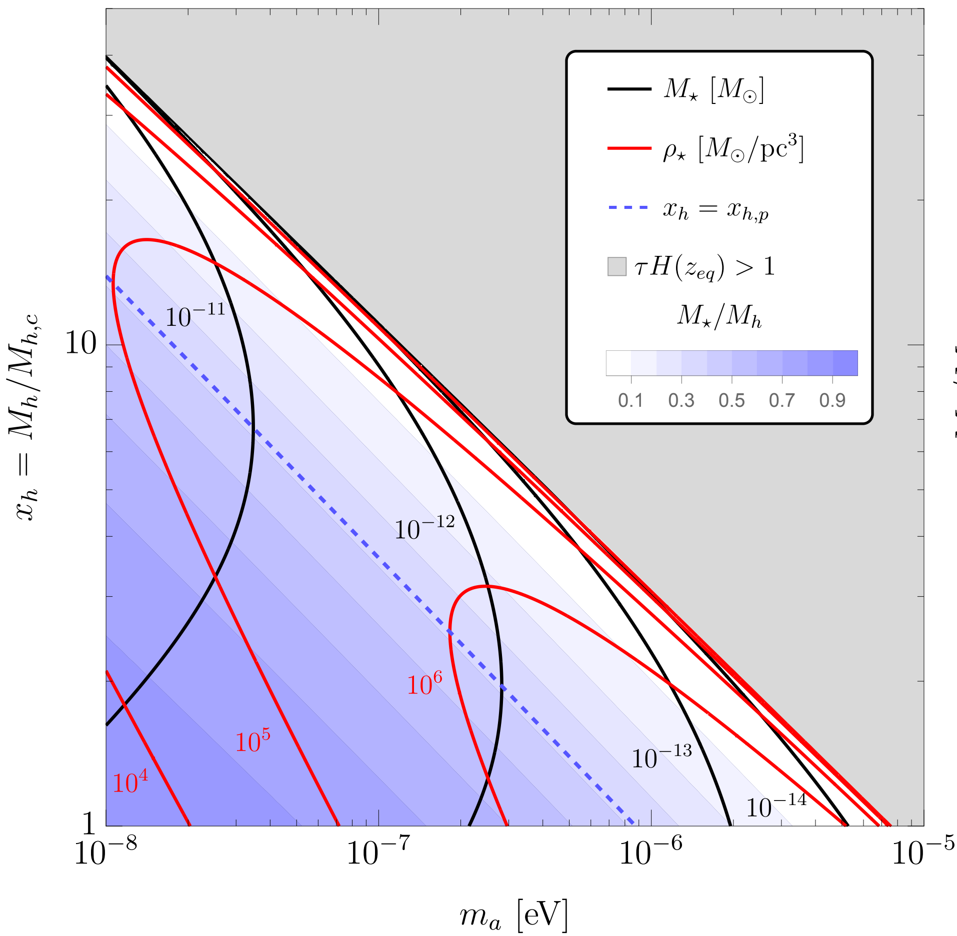


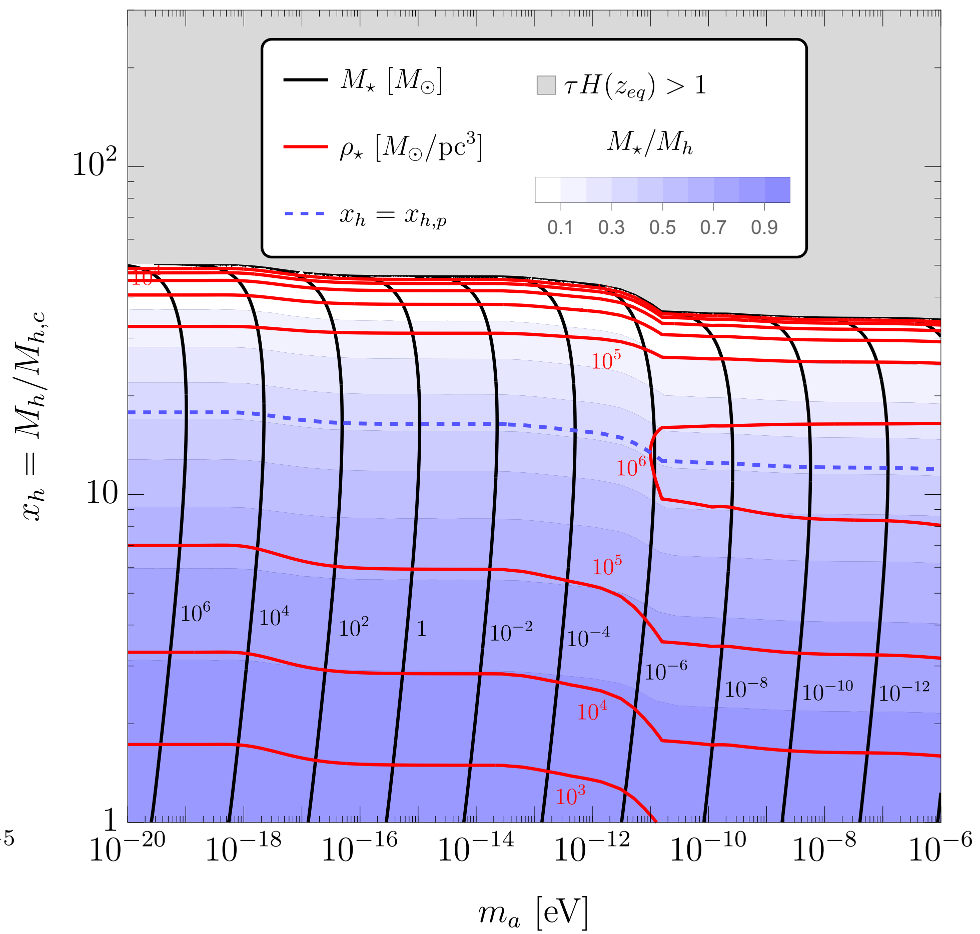
Gorghetto et al, 2405.19389

Axion star in minihalos

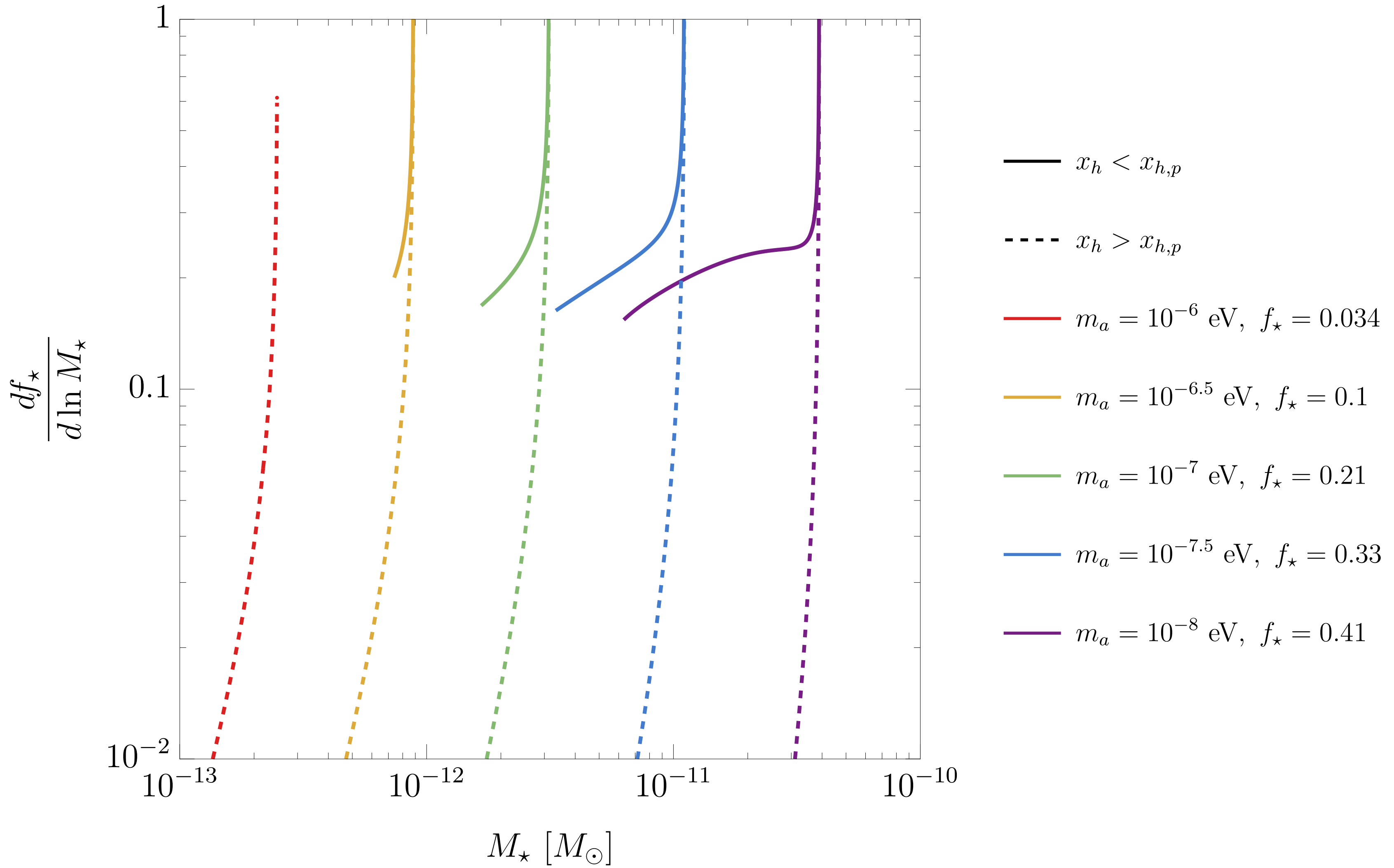
QCD Axion

ALP

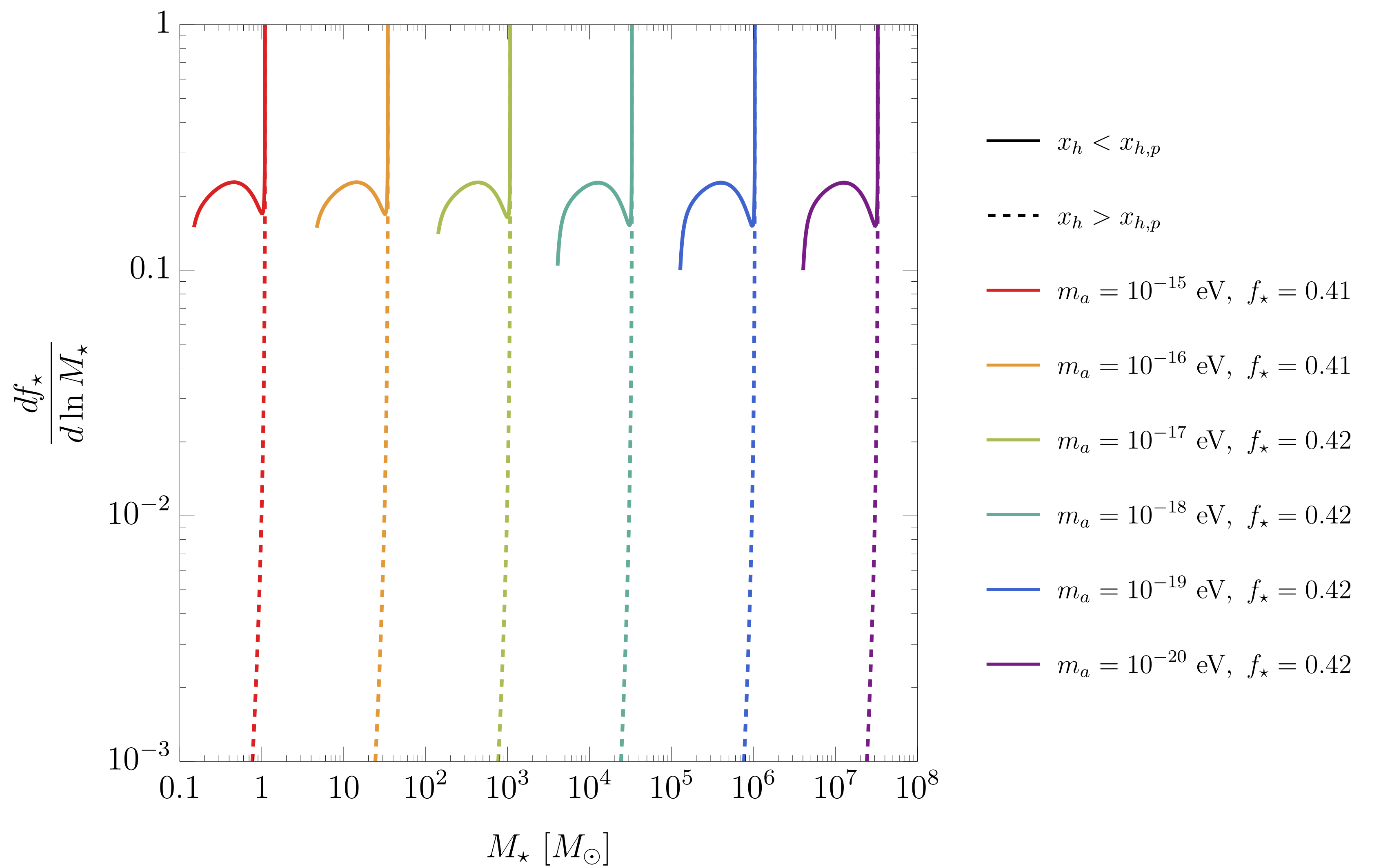




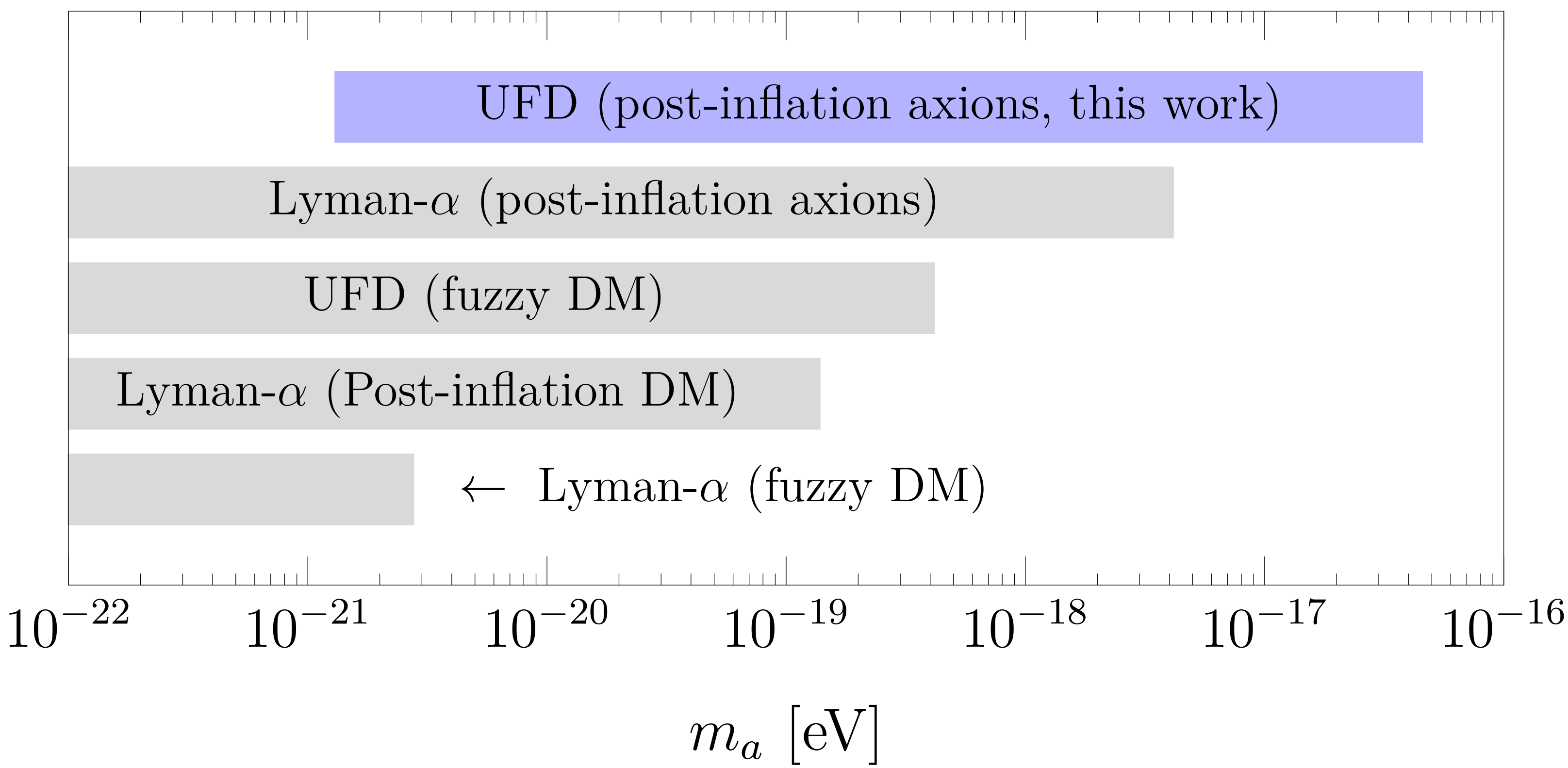
Axion star mass functions (QCD axion)



Axion star mass functions (ALP)



ALP mass constraints



- We put constraints on ALP masses from heating of ultra-faint dwarfs (See Hari's talk)

Graham and Ramani, 2311.07654, 2404.01378

Conclusions

- We calculate axion star mass function analytically
- The resulting mass function gives constraints on axion masses via heating of ultra-faint dwarf galaxies
- The mass function can be used for future gravitational searches of axion stars

THANK YOU