AXION STARS:
MASS FUNCTIONS AND CONSTRAINTS

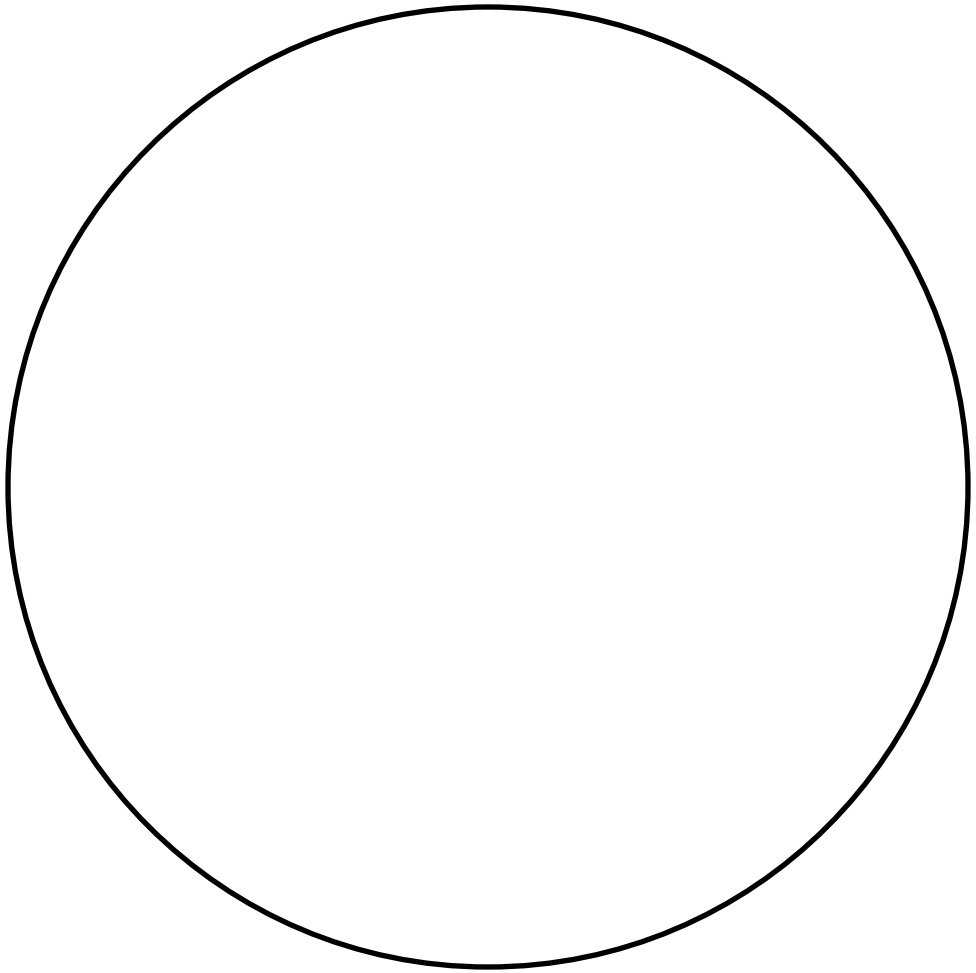
Based on arXiv:2406.09499
with Patrick J. Fox and Huangyu Xiao

Jae Hyeok Chang
Fermilab and UIC

2024/11/18 The 12th KIAS Workshop on Particle Physics and Cosmology

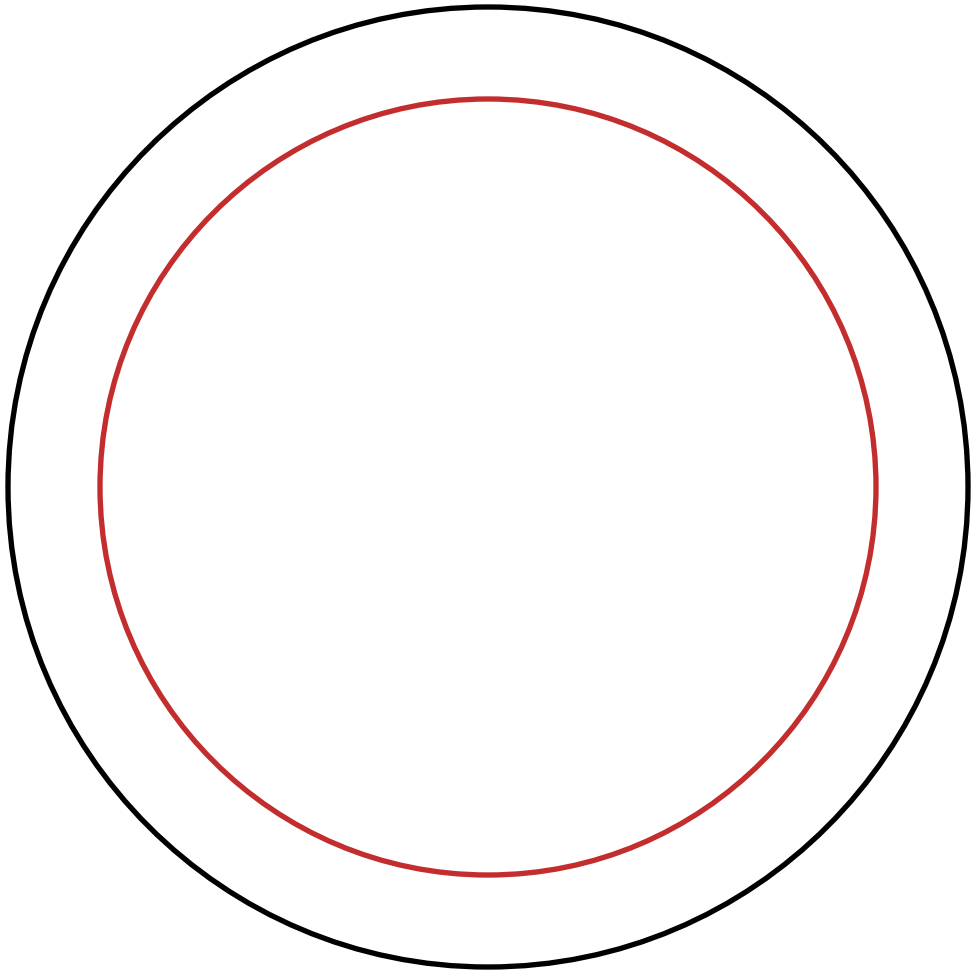
HOW ARE NORMAL STARS FORMED?

A virialized CDM halo



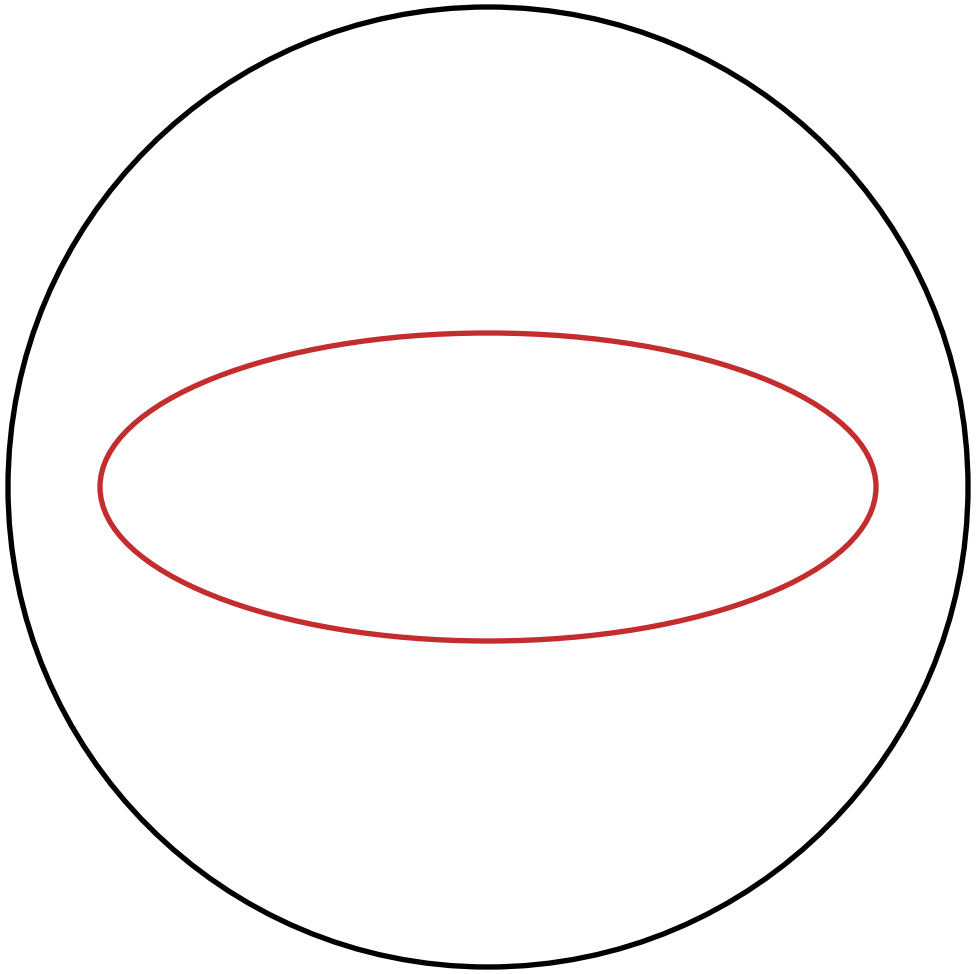
- Matter perturbations evolve only logarithmically in RD
- But they grow with power-law in MD
- For CDM, virialization happen deep in MD
- Bigger mass halos form later times

Baryons in CDM halo



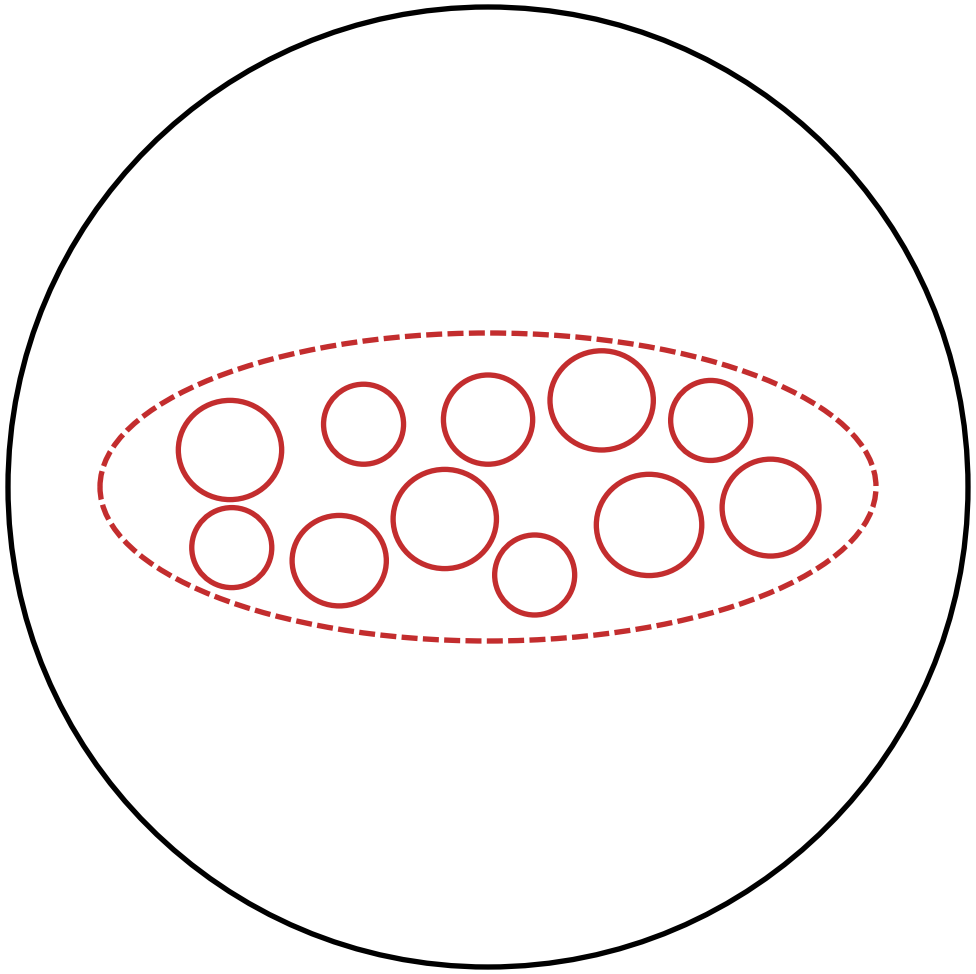
- Baryon perturbations cannot grow before recombination
- After that, baryons fall into the CDM potential well
- Baryon perturbations follow CDM perturbations
- Baryon clouds form in CDM halos

Baryons collapse into a disk



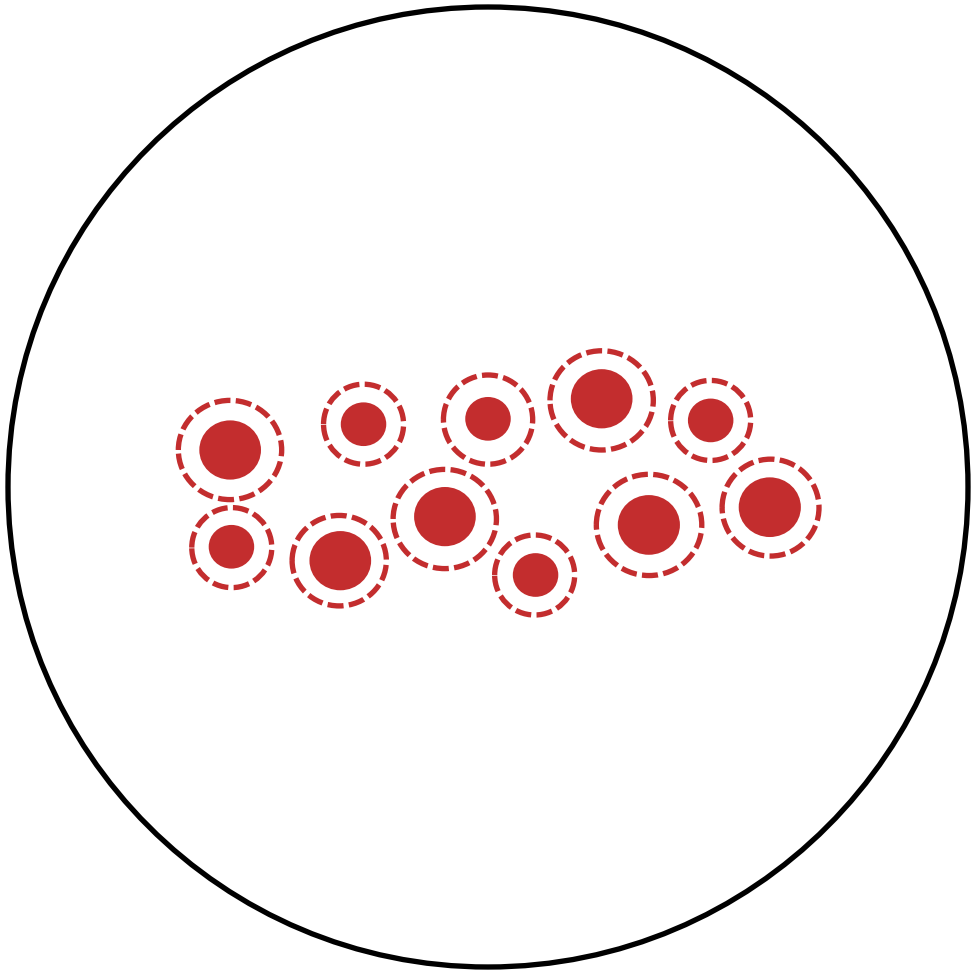
- CDM can form halo since they have no (or weak) self-interactions
- Baryons collide each other and collapse
- They collapse into a disk due to their angular momentum

Fragmentation



- As baryon number density increases, cooling process becomes effective
- Cooling processes make Jeans mass smaller
- Baryons start to fragment

Star formation



- Fragmentation stops if each blob becomes optically thick
- Each blob forms a stable compact object
- Need interactions, especially cooling

For dark star formation from fragmentation, see JHC et al, 1812.07000

HOW ARE AXION STARS FORMED?

Two axion DM scenarios:

Misalignment before inflation

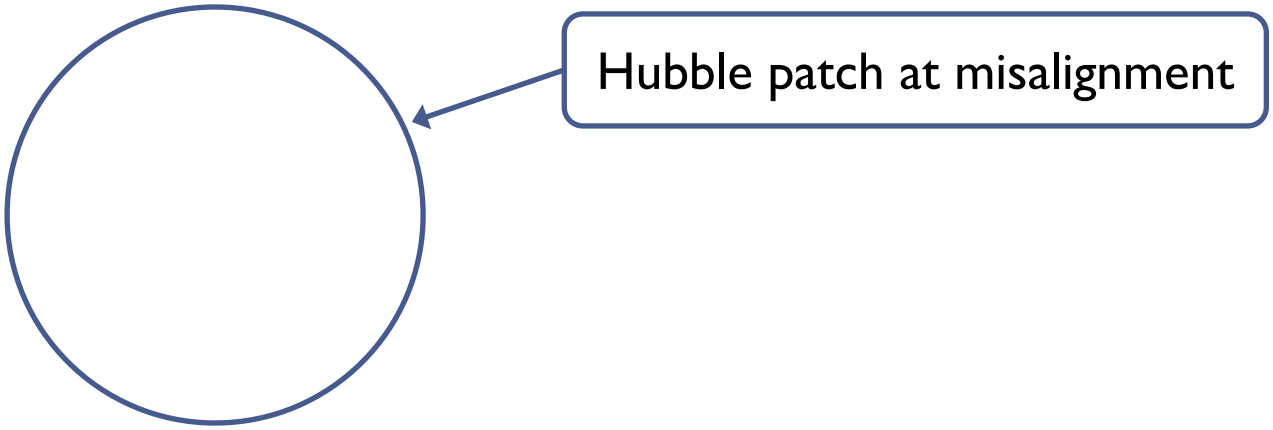
Misalignment after inflation

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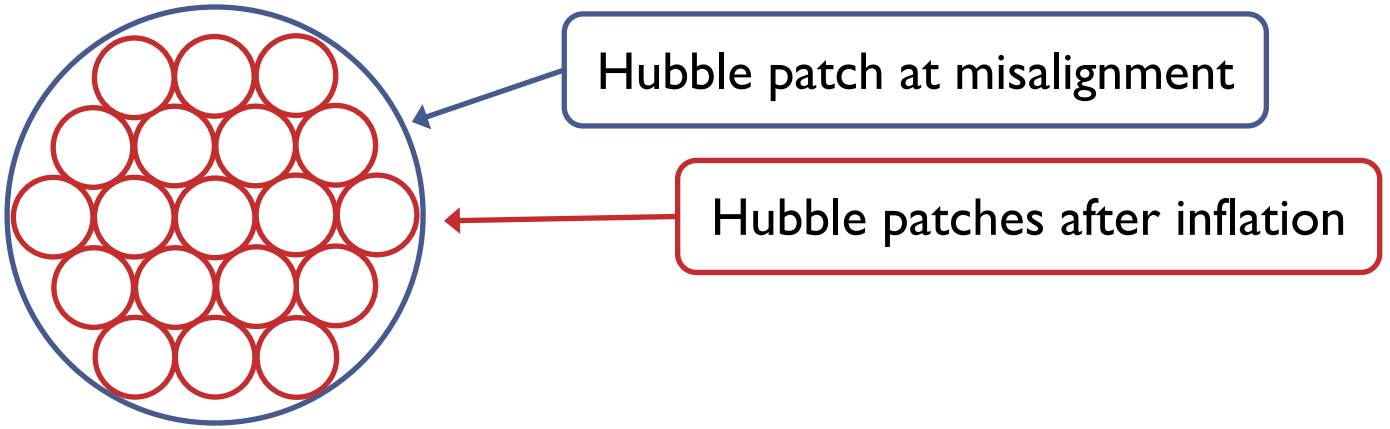
Misalignment before inflation

Misalignment after inflation

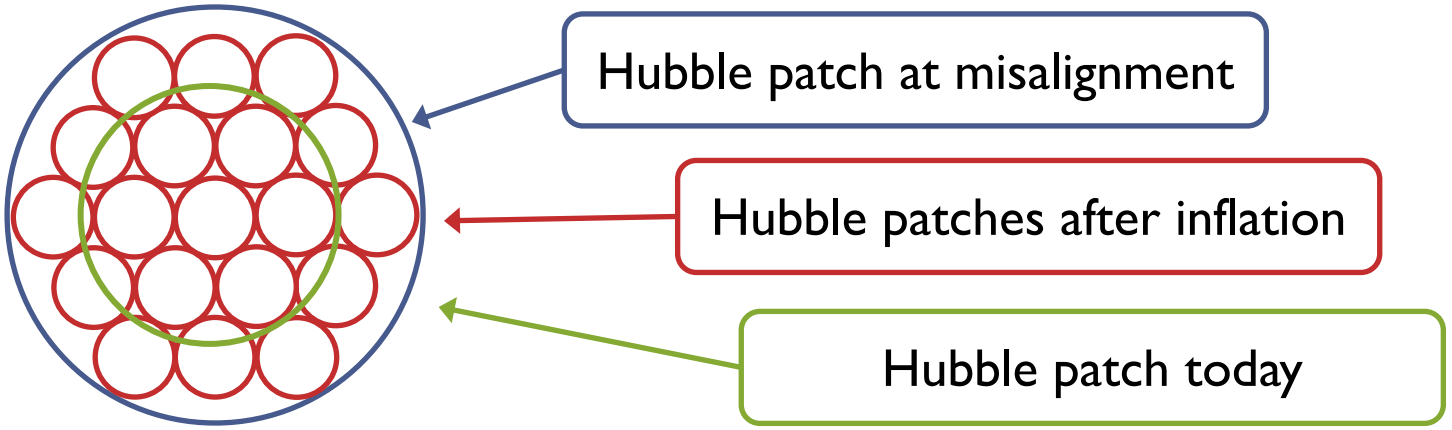
Misalignment before inflation



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Misalignment before inflation



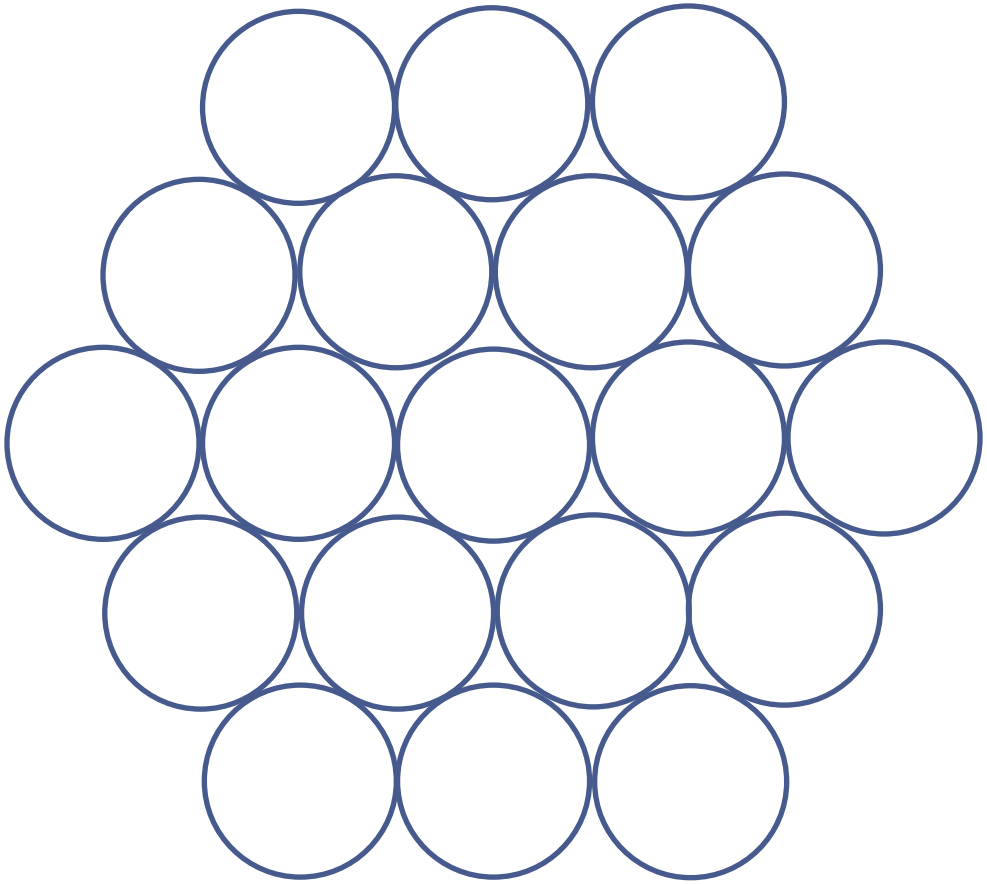
- The Hubble patch today has same θ_i value
- No isocurvature perturbations
- Same as the CDM case: Needs a cooling process, but axions do not have such processes

Two axion DM scenarios:

Misalignment before inflation

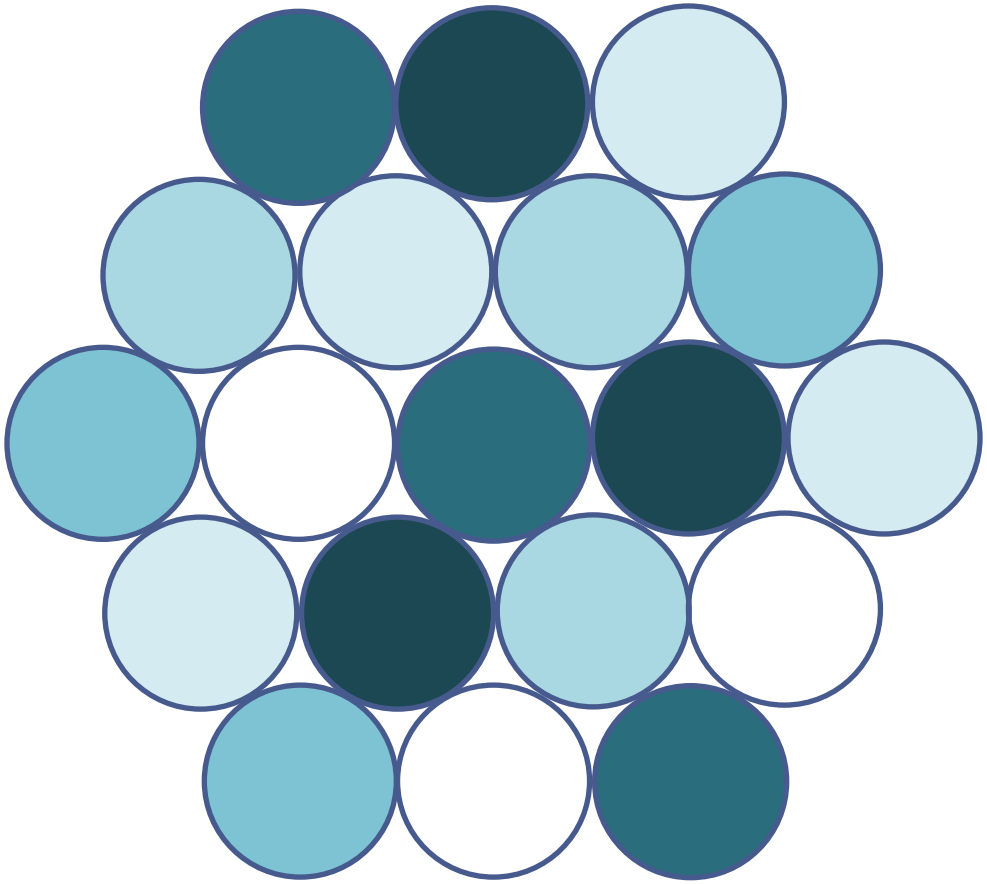
Misalignment after inflation

Misalignment after inflation



- Different Hubble patches after inflation

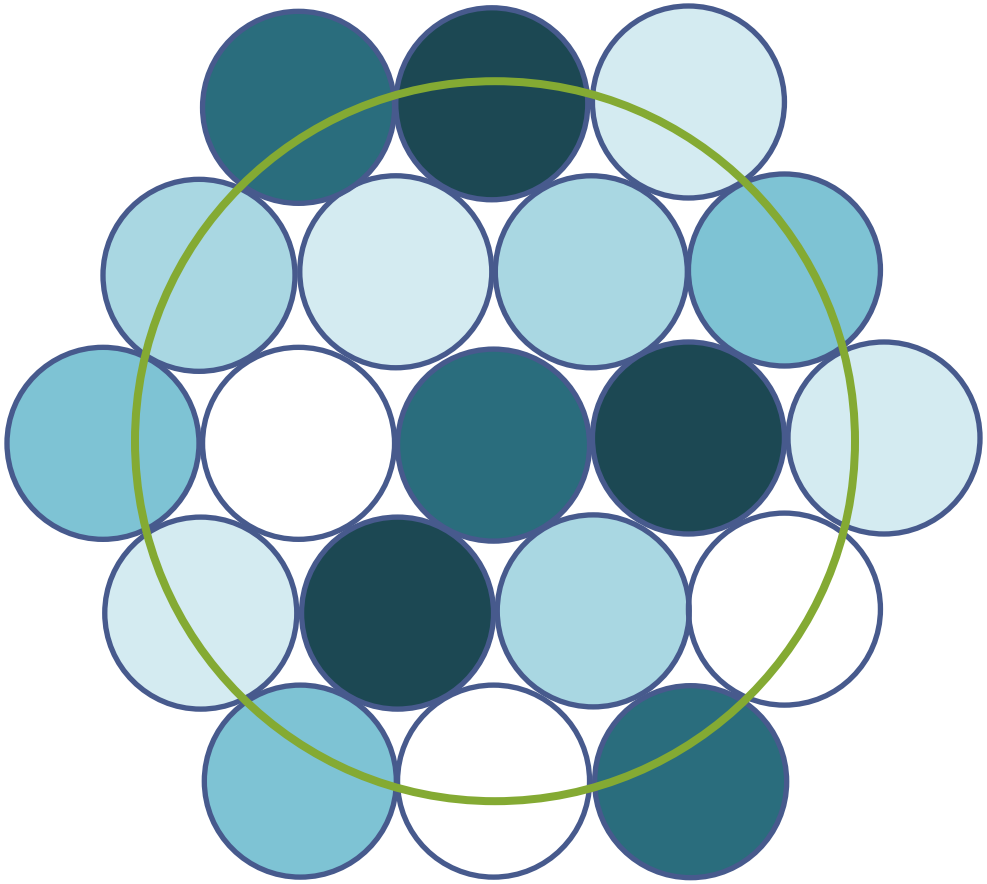
Misalignment after inflation



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

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

Misalignment after inflation



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

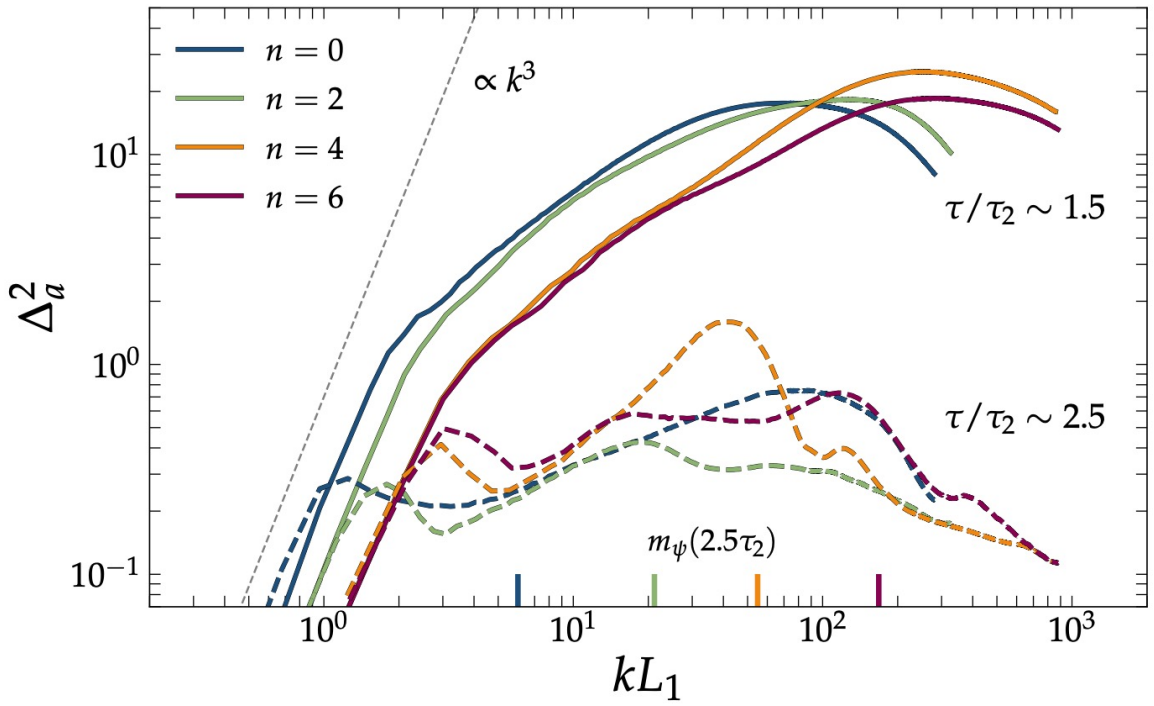
$$\theta_i \in (-\pi, \pi)$$

- Axions can have large isocurvature perturbations at small scales

White-noise spectrum

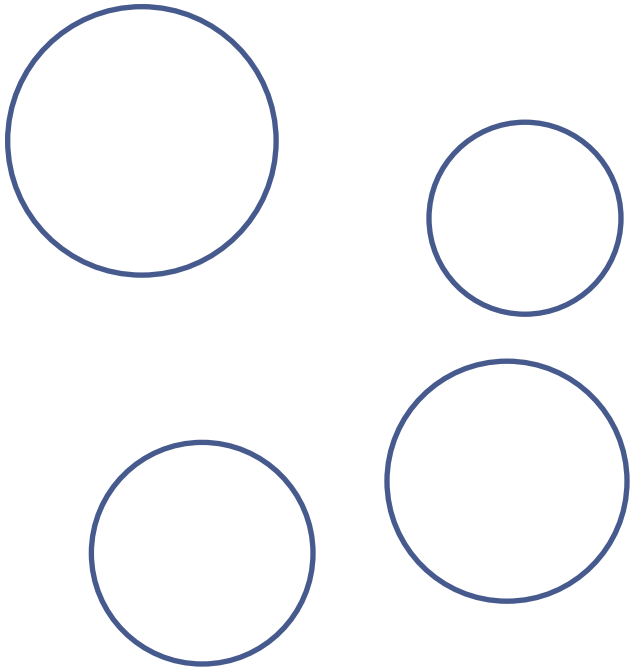
- Misalignment after inflation yields a white-noise density spectrum, which has a flat power spectrum

$$\Delta^2(k) = \frac{k^3}{2\pi^2} P(k) = A_0 \left(\frac{k}{k_0}\right)^3 \Theta(k_0 - k)$$



O'Hare et al, 2112.05117

Axion minihalos



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

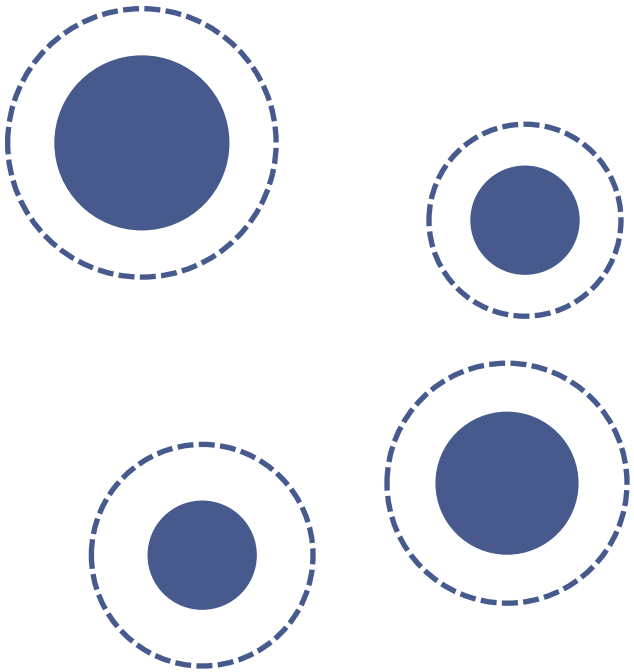
- Such minihalos are already light:

$$M_{h,c} = \frac{4\pi}{3} A_0 \left(\frac{1}{k_0}\right)^3 \bar{\rho}_{a,0}$$

$$\sim 10^{-14}\, M_\odot \left(\frac{\mu\text{eV}}{m_a}\right)^{3/2}$$

- 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 in each minihalo

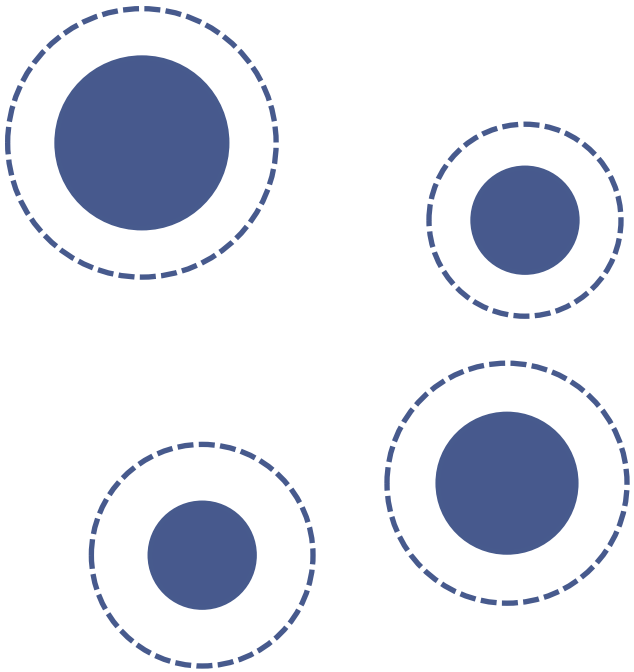
$$\tau_{\rm gr} \sim \left(f_{BE} n \sigma_{\rm gr} v\right)^{-1}$$

Levkov et al, 1804.05857

- Due to large f_{BE}, gravitational interaction is enough to collapse

- No need fragmentation, so no need cooling process

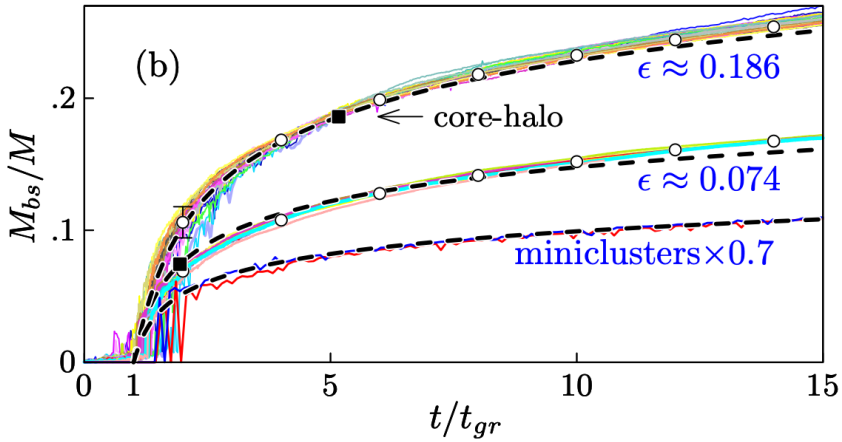
Axion stars



- Axion star mass in a given halo mass M_h after time t is

$$M_\star(t) = M_h\, x_\star(t)$$

- $x_\star(t)$ is the axion star evolution function depending on m_a and M_h
- $x_\star(\tau_{\rm gr}) = 0$ and $x_\star(\infty) = 1$



Dmitriev et al, 2305.01005

Goal of this work

- Getting the mass function of axion stars today
- Accurate calculation requires heavy numerical simulations, particularly for 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

MASS DISTRIBUTION OF AXION STARS

To get the axion star mass analytically

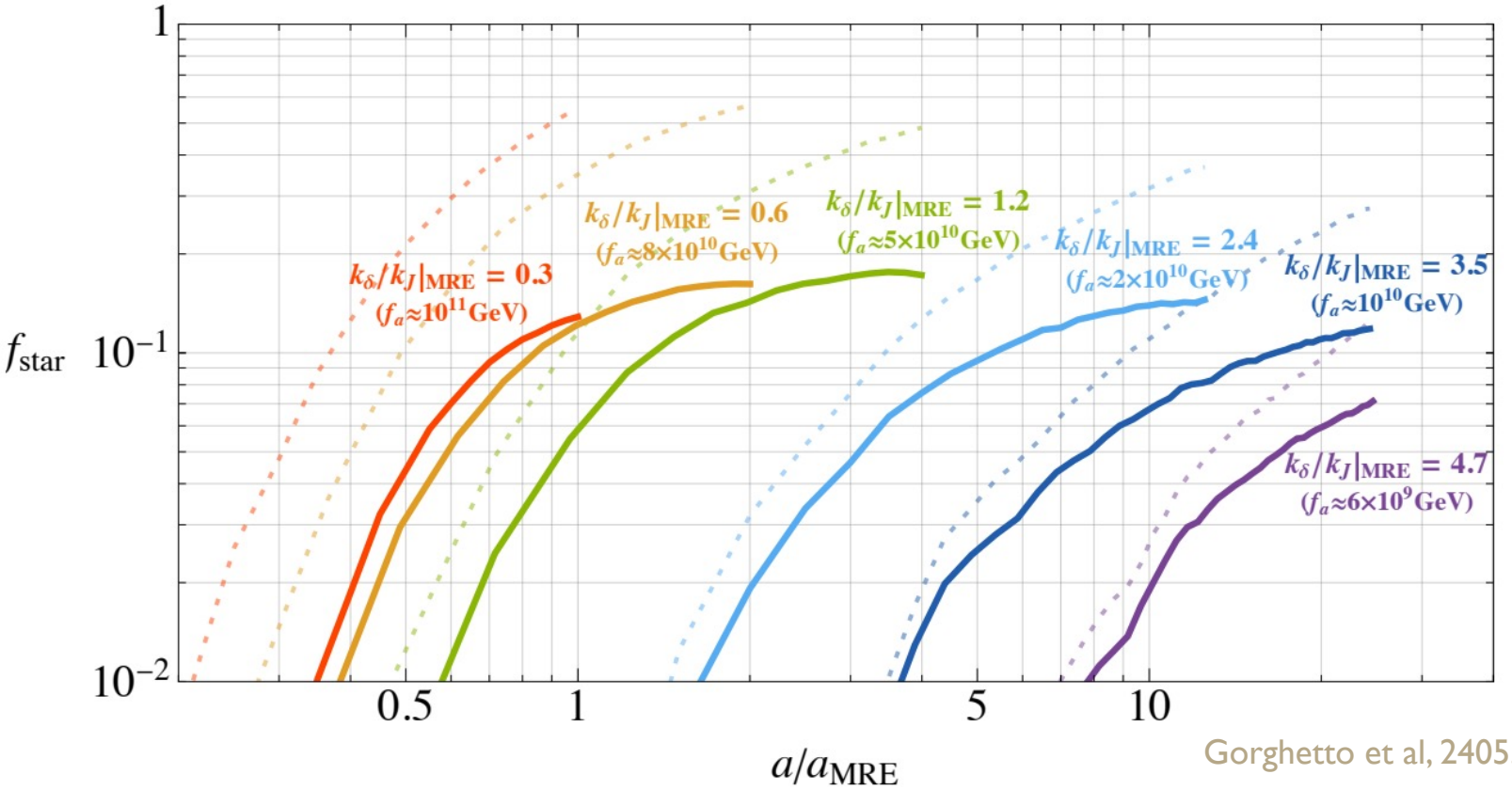
- We consider axion minihalos at the time of matter-radiation equality and allow an axion star to evolve over one Hubble time within each minihalo

- 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

To get the axion star mass analytically

- We consider axion minihalos at the time of matter-radiation equality and allow an axion star to evolve over one Hubble time within each minihalo



Gorghetto et al, 2405.19389

Axion star mass function

$$\frac{df_\star}{dM_\star} = \frac{M_\star}{M_h}\frac{df_h}{dM_h}\frac{dM_h}{dM_\star}$$

- $f_\star = \rho_\star/\rho_{\rm DM}$ and $f_h = \rho_h/\rho_{\rm DM}$: mass densities

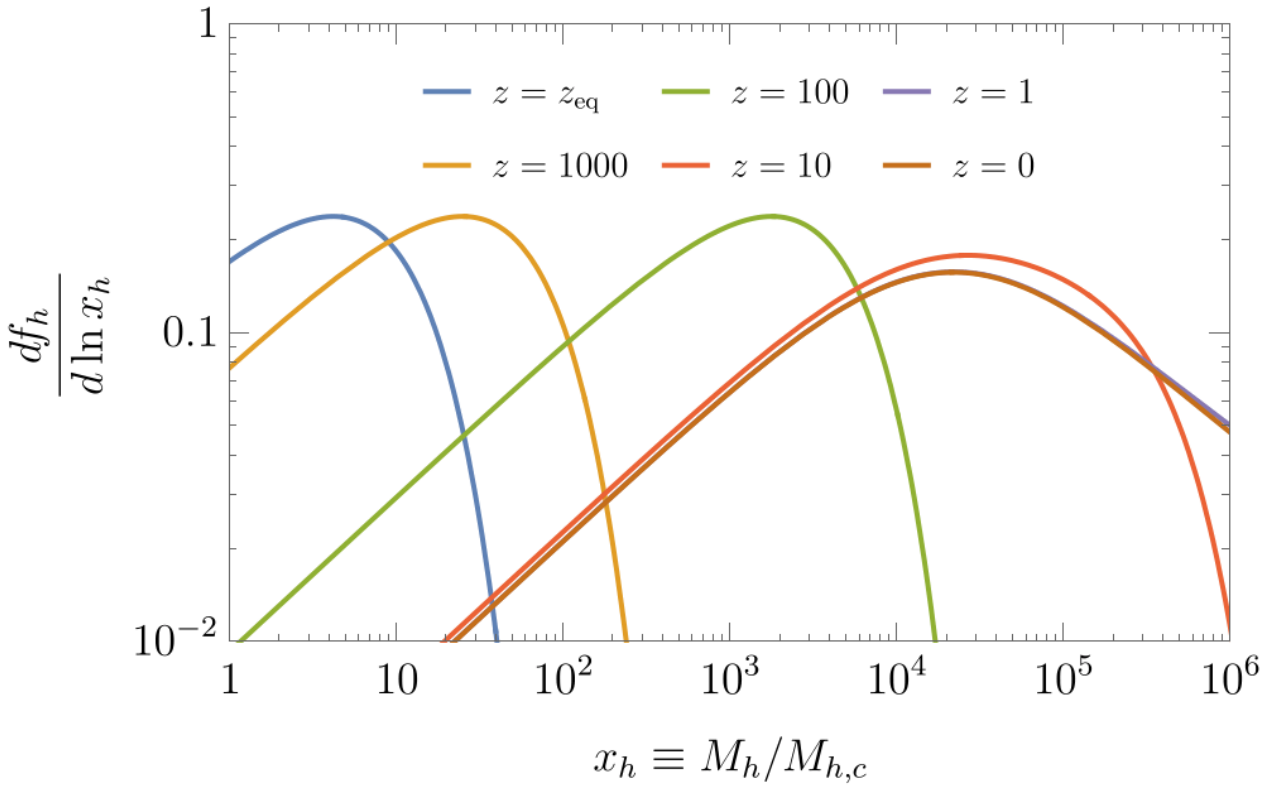
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- $f_\star = \rho_\star/\rho_{\rm DM}$ and $f_h = \rho_h/\rho_{\rm DM}$: mass densities
- $\frac{df_h}{dM_h}$ is the mass distribution of axion minihalos

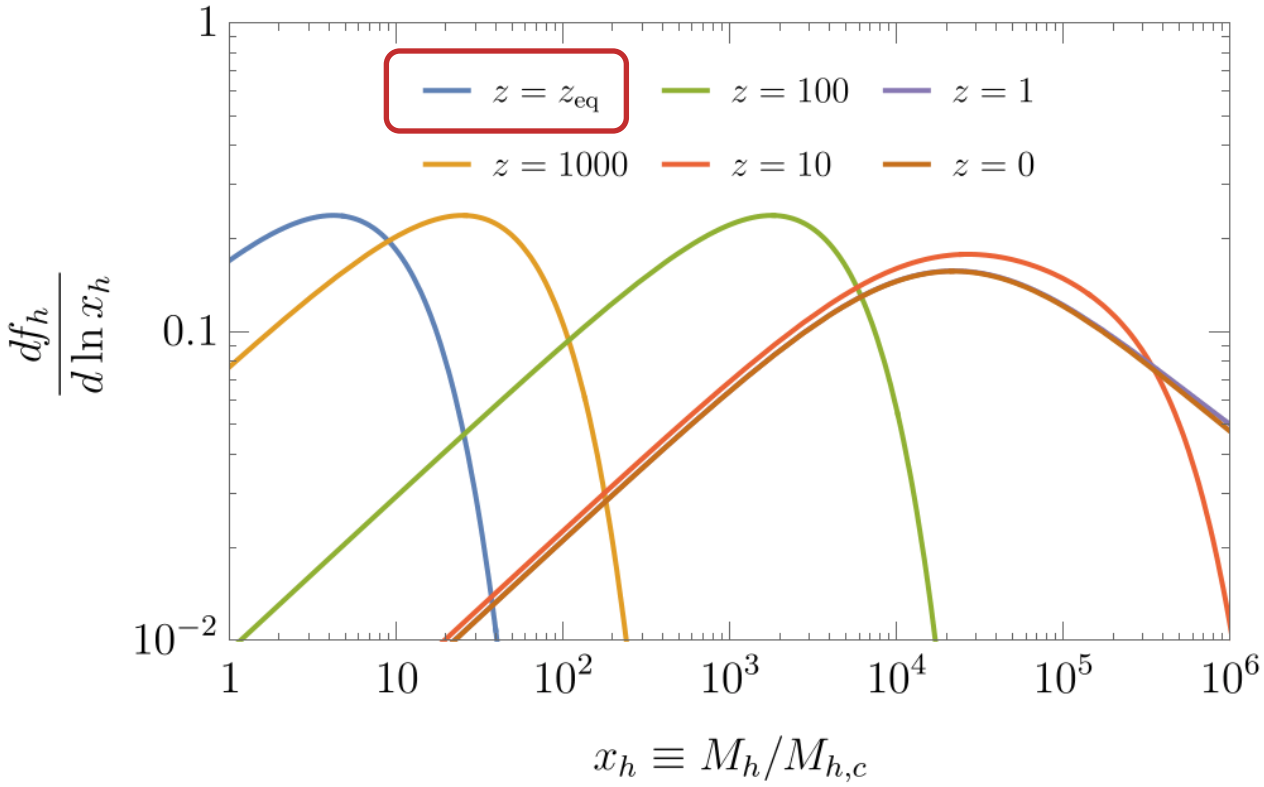
Mass distribution of axion minihalos

- From the power spectrum, we can can calculate the mass function of axion minihalos by using the Press-Schechter formalism



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We choose the mihihalo mass function at $z = z_{\rm eq}$

Axion star mass function

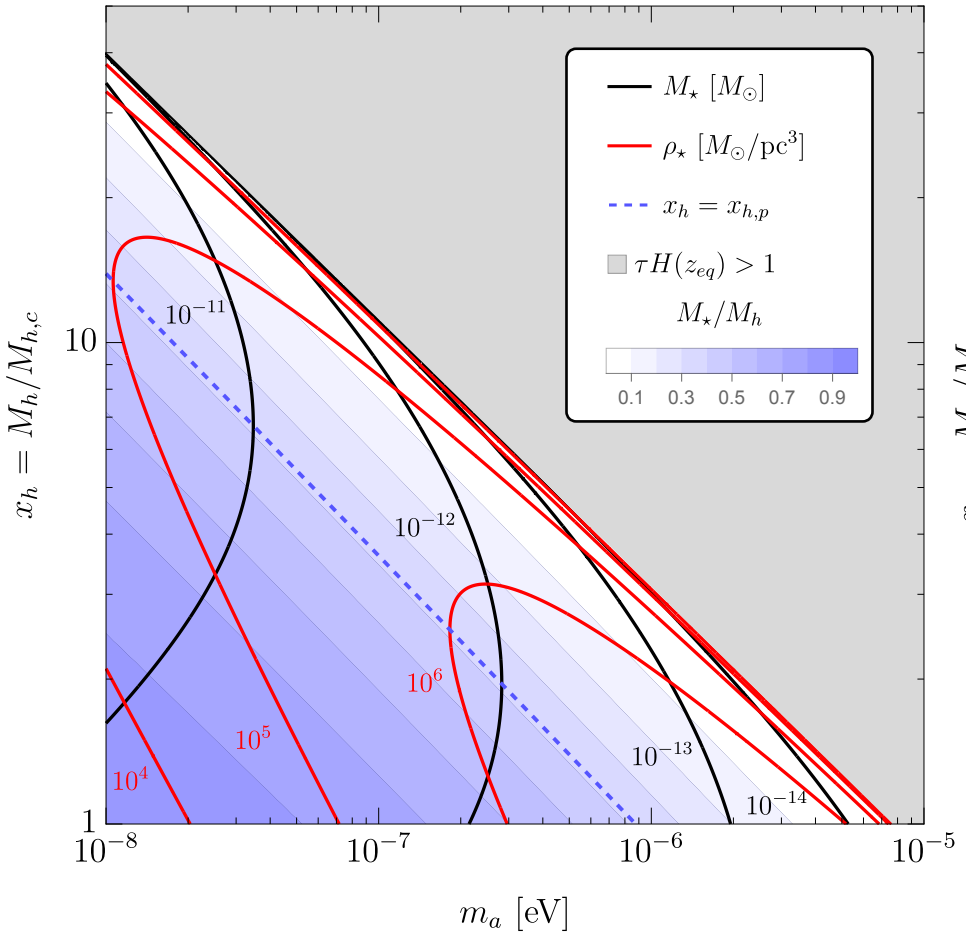
$$\frac{df_\star}{dM_\star} = \frac{M_\star}{M_h}\frac{df_h}{dM_h}\frac{dM_h}{dM_\star}$$

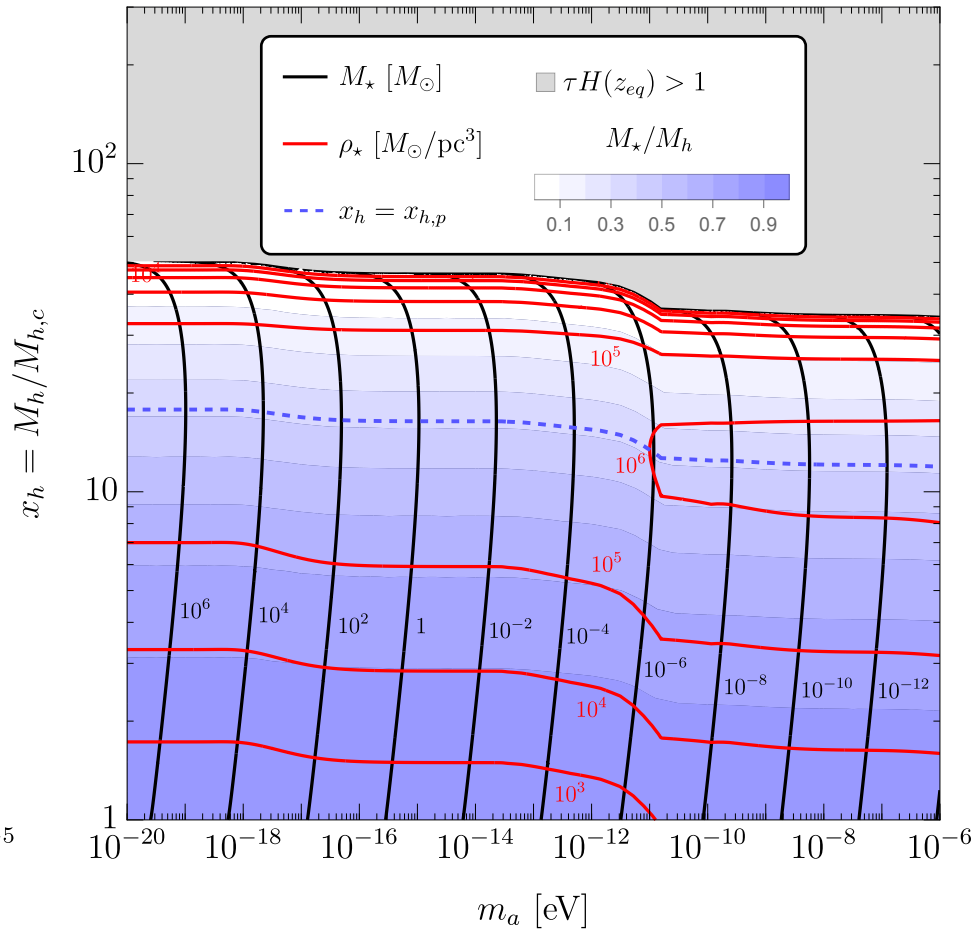
- $f_\star = \rho_\star/\rho_{\rm DM}$ and $f_h = \rho_h/\rho_{\rm DM}$: mass densities
- $\frac{df_h}{dM_h}$ is the mass distribution of axion minihalos
- $\frac{dM_h}{dM_\star}$ can be obtained from $M_\star$ as a function of M_h

Axion star in minihalos

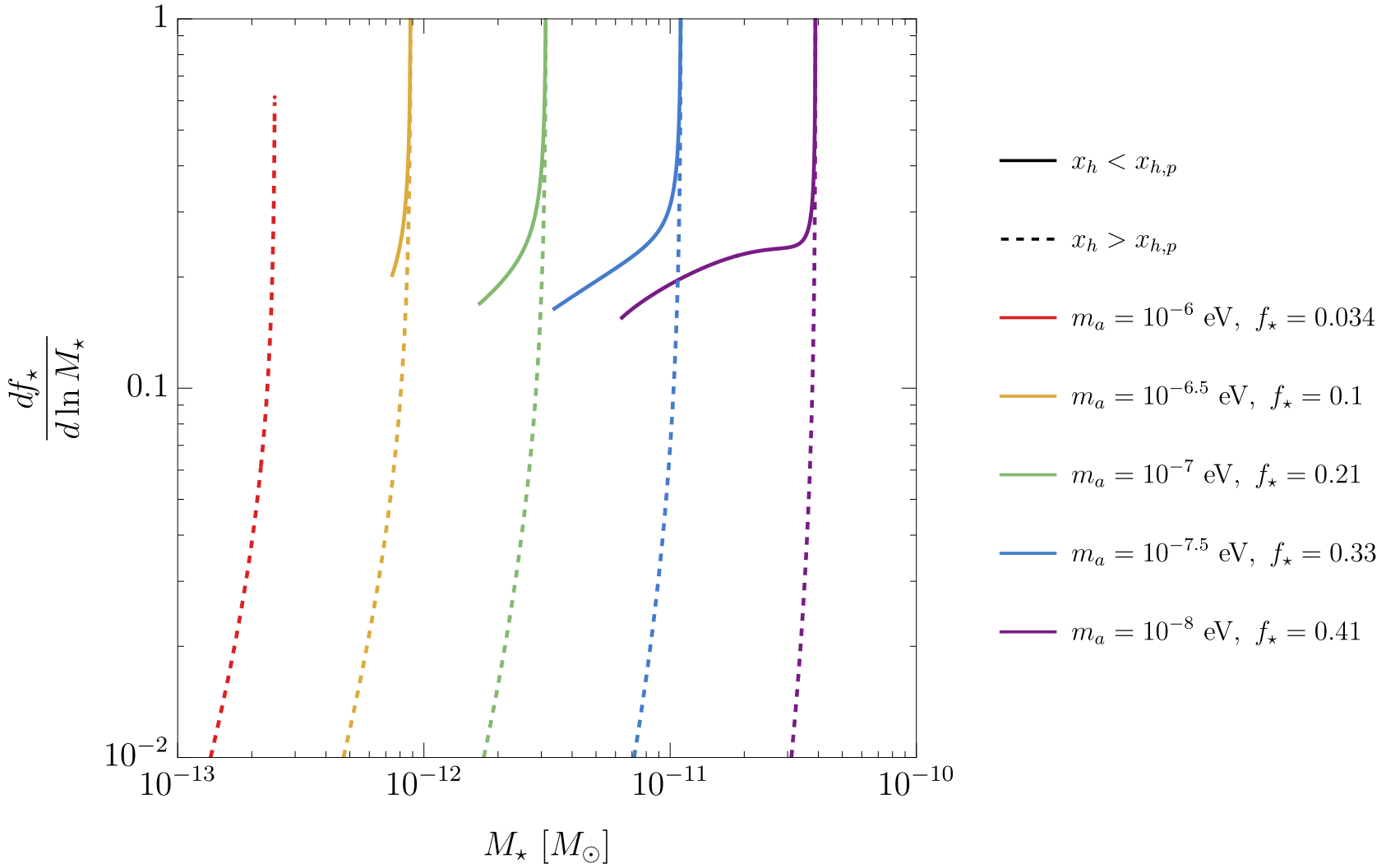
QCD Axion

ALP

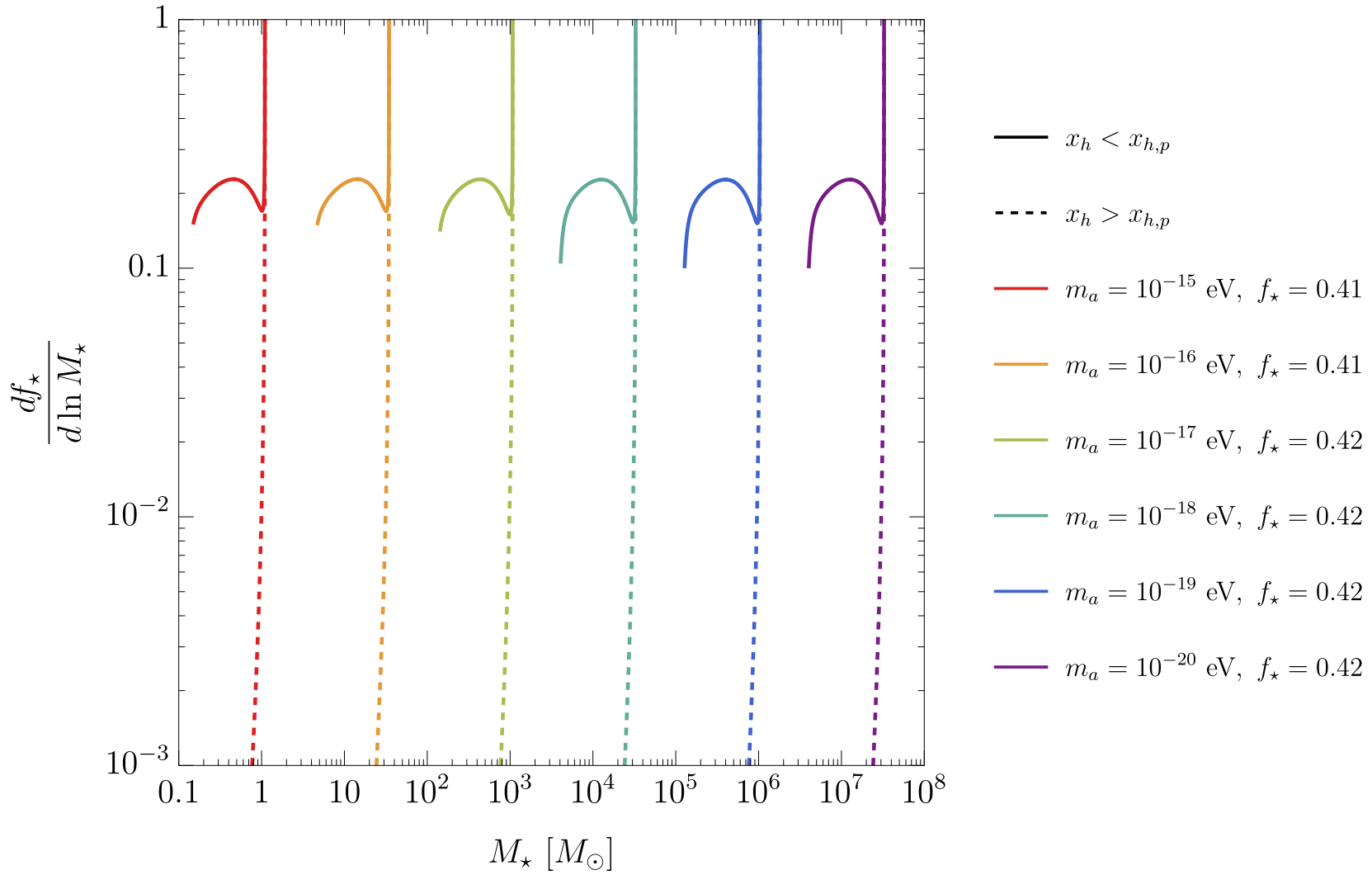




Axion star mass functions (QCD axion)



Axion star mass functions (ALP)



CONSTRAINTS

QCD axion stars

- Typical masses and densities:
  - $M_\star = 10^{-14} - 10^{-10}\, M_\odot$
  - $\rho_\star = 10^{4} - 10^{6}\, M_\odot/\mathrm{pc}^3$

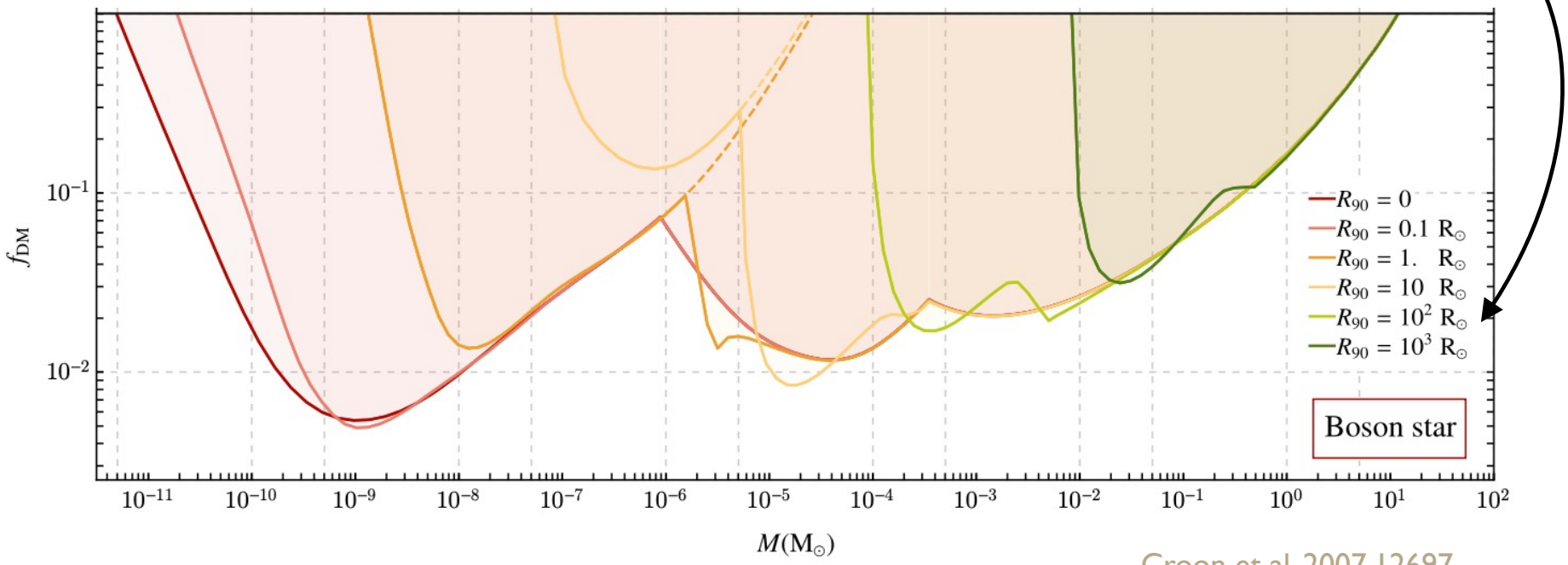
- The best way to detect these mass range is microlensing observations

- However, the current observation data cannot give constraints since the density is too low

QCD axion stars

- Typical masses and densities:
  - $M_\star = 10^{-14} - 10^{-10}\ M_\odot$
  - $\rho_\star = 10^{4} - 10^{6}\ M_\odot/\mathrm{pc}^3$

$M_\star = 10^{-10} M_\odot$ and $\rho_\star = 10^6 M_\odot/\mathrm{pc}^3$
Corresponds to $R = 10^2\ R_\odot$



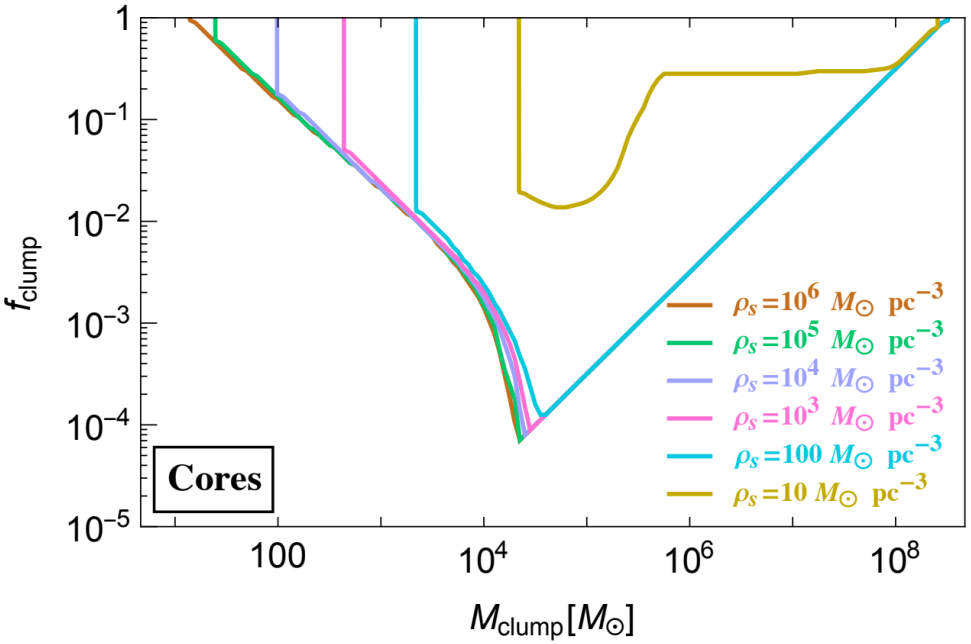
Croon et al, 2007.12697

ALP stars

- Typical masses and densities for $10^{-20}\ \mathrm{eV} < m_a < 10^{-16}\ \mathrm{eV}$:
  - $M_\star = 10 - 10^7\ M_\odot$
  - $\rho_\star = 10^4 - 10^6\ M_\odot/\mathrm{pc}^3$

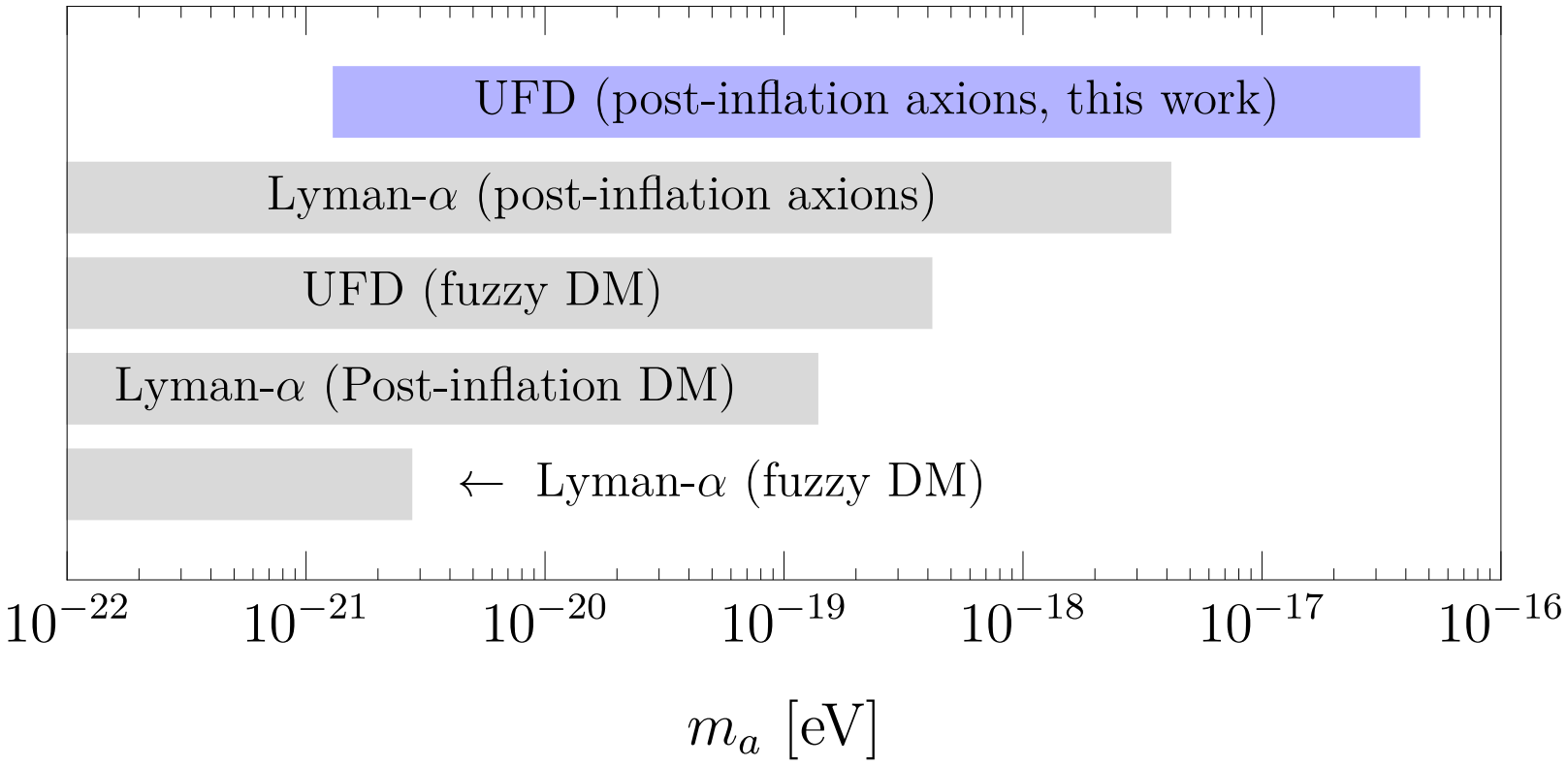
- The best way to detect these mass range is heating of ultrafaint dwarfs (UFD)

Graham and Ramani, 2311.07654, 2404.01378



ALP mass constraints

$$\int f_{\mathrm{UFD}}^{-1}(M_\star, \rho_\star)\, \frac{df_\star}{dM_\star}\, dM_\star < 1$$



CONCLUSIONS

Conclusions

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

Future Works

- Gravitational searches of axion stars in future experiments
  - Microlensing
  - Pulsar Timing Arrays

- Radio signal of axion stars
  - From axinovae
  - From stimulated decay

THANK YOU