AXION STARS:

MASS FUNCTIONS, CONSTRAINTS, AND SIGNALS

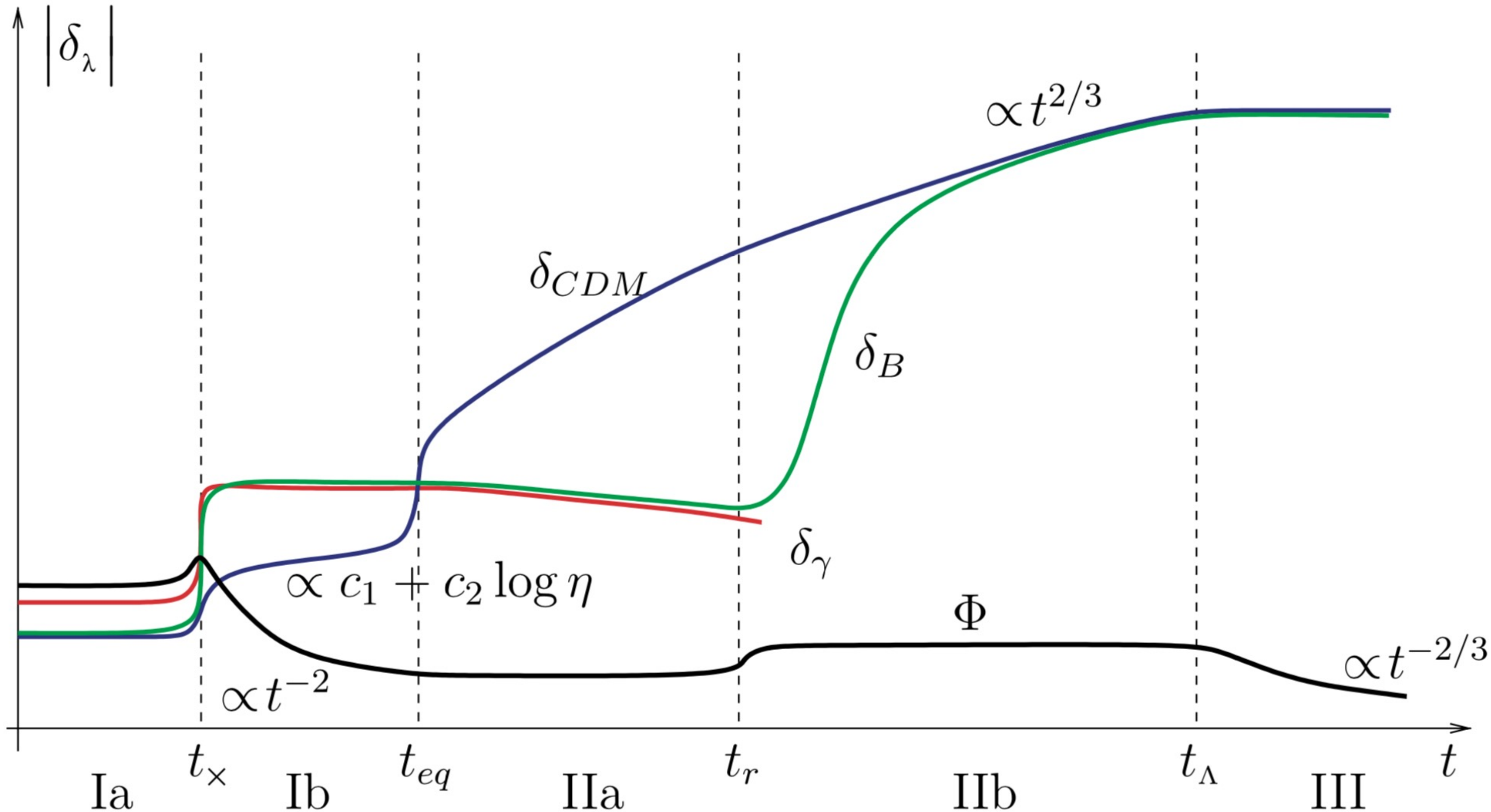
Based on
arXiv:2406.09499 with Patrick J. Fox and Huangyu Xiao
arXiv:26xx.xxxxx with Katelin Schutz, Yitian Sun, and Huangyu Xiao

Jae Hyeok Chang
Seoul National University

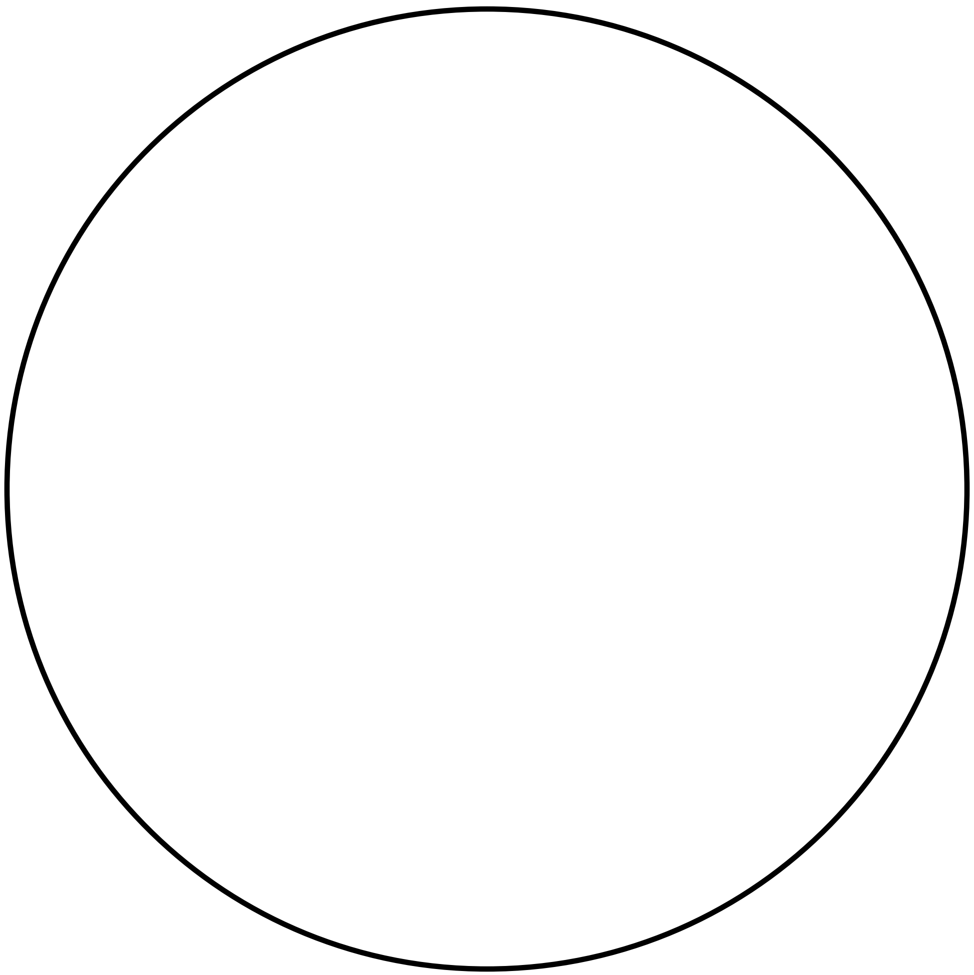
2026.07.28 Axions in Seoul 2026

HOW ARE NORMAL STARS FORMED?

Perturbation growth

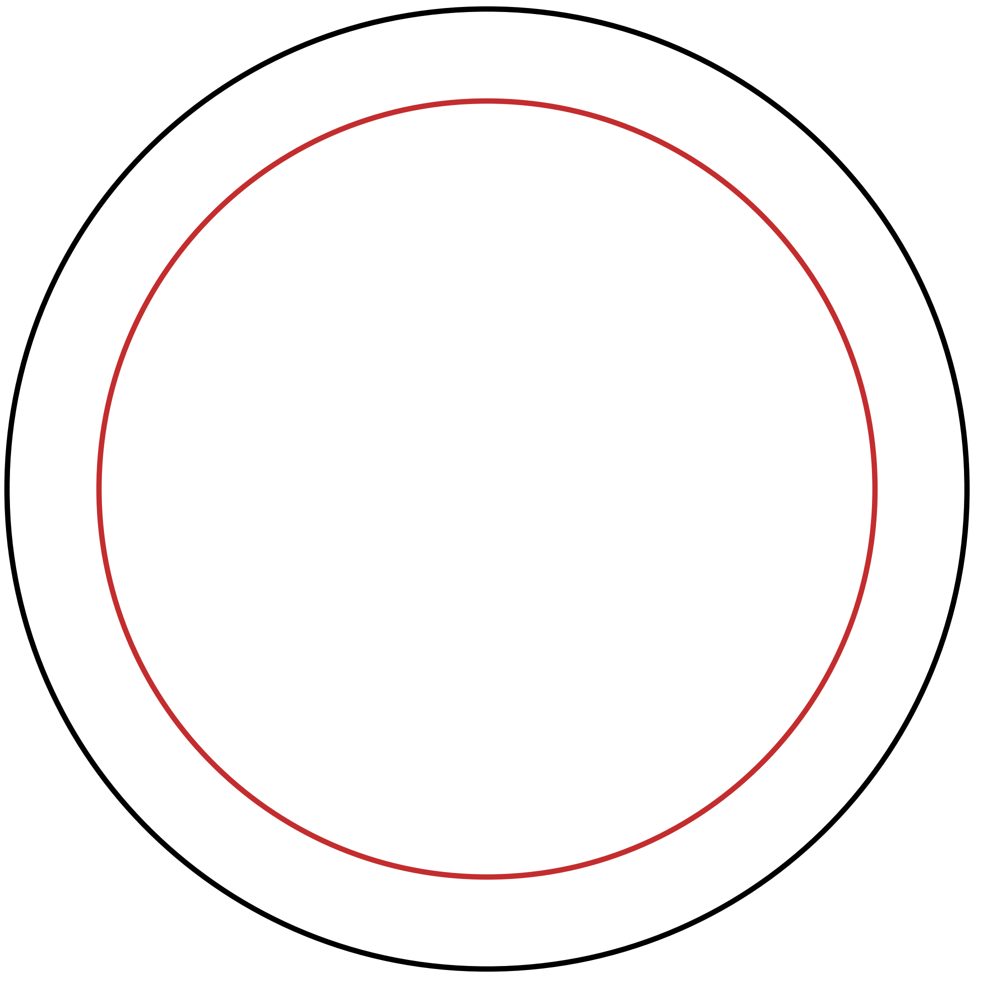


A virialized CDM halo



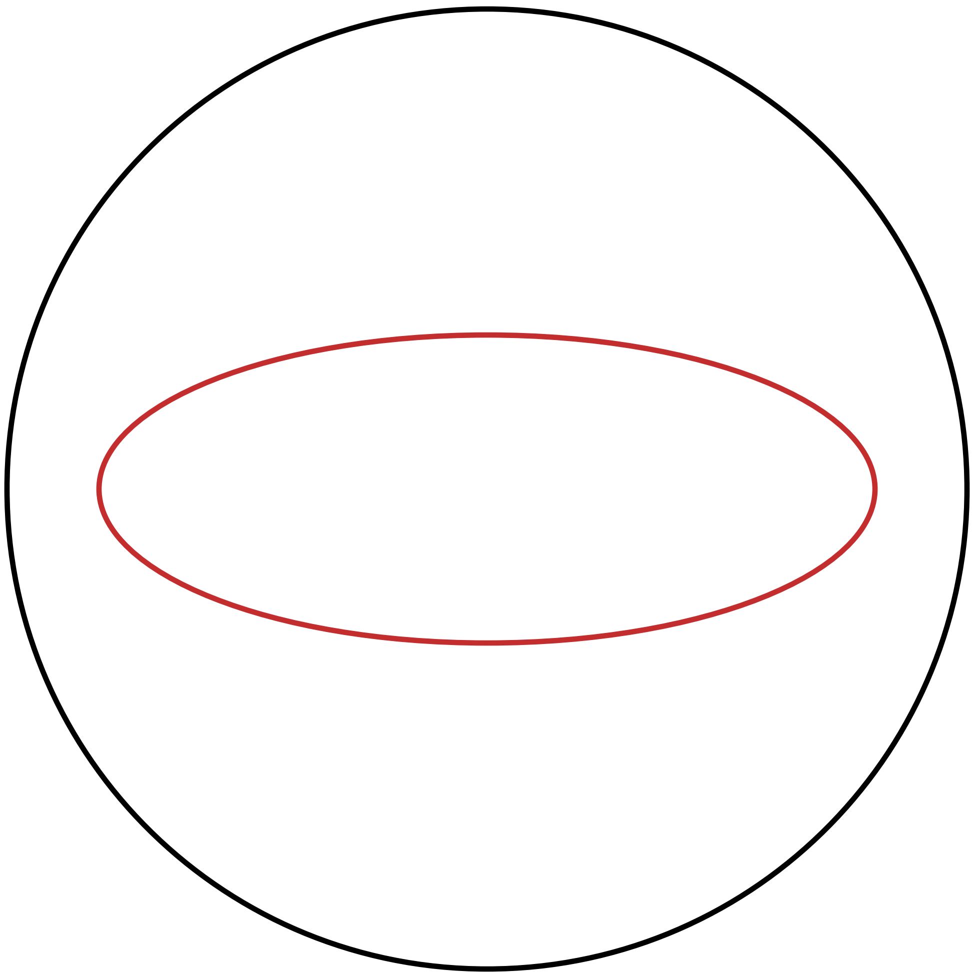
- CDM halo with $\delta \gg 1$ deep in matter-domination

Baryons in CDM halo



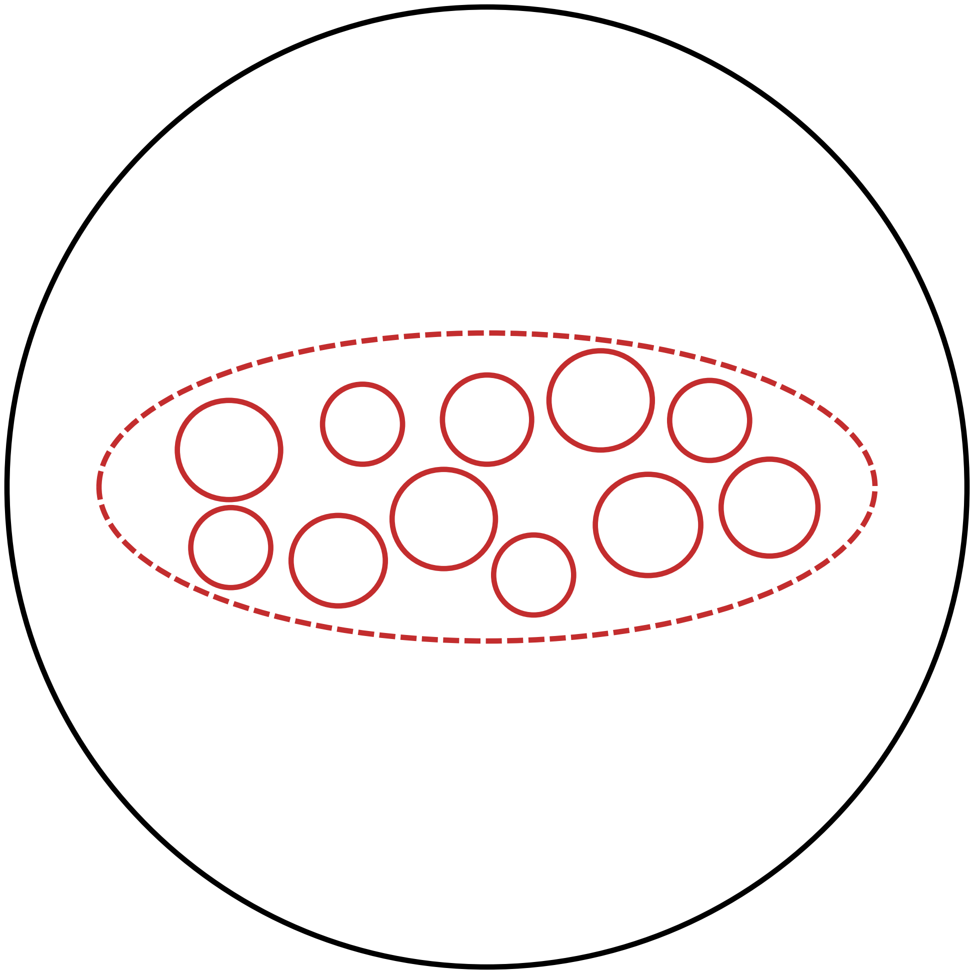
- CDM halo with $\delta \gg 1$ deep in matter-domination
- Baryons fall into the CDM potential well

Baryons collapse into a disk



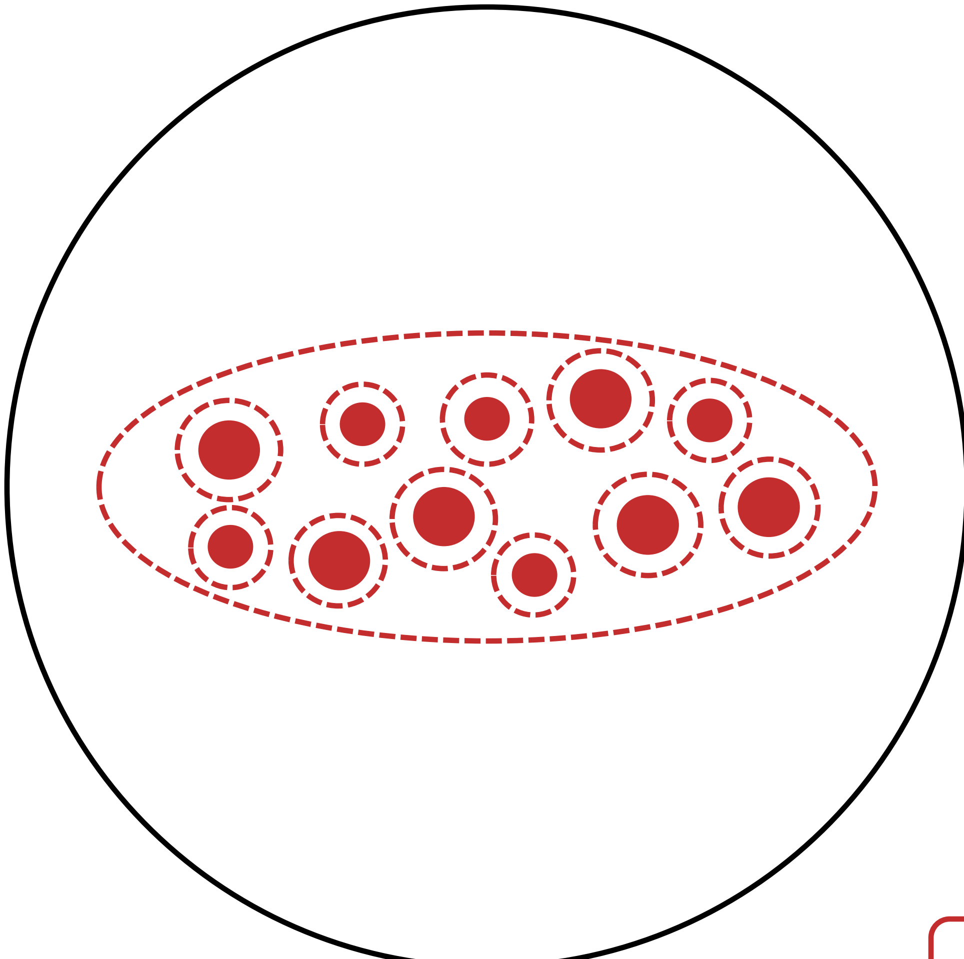
- CDM halo with $\delta \gg 1$ deep in matter-domination
- Baryons fall into the CDM potential well
- They collapse into a disk due to interactions and their angular momentum

Fragmentation



- 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

Star formation



- 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 JHC et al, 1812.07000

HOW ARE AXION STARS FORMED?

Two axion DM scenarios:

Misalignment before inflation

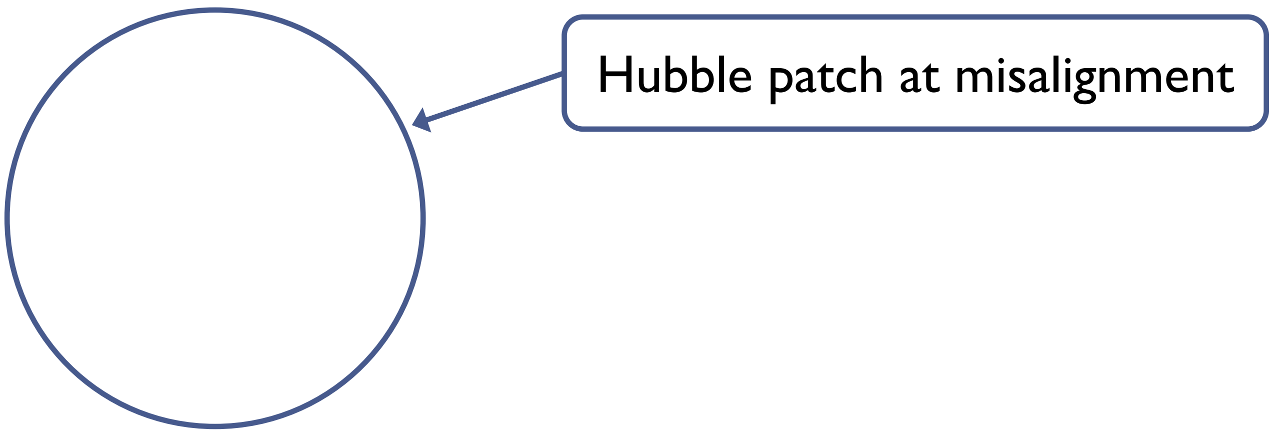
Misalignment after inflation

Two axion DM scenarios:

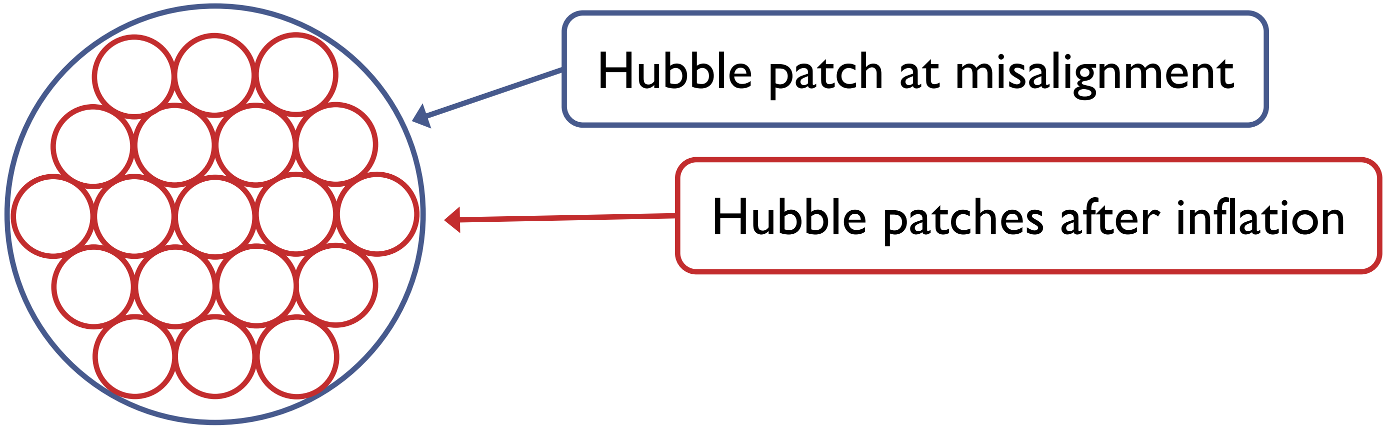
Misalignment before inflation

Misalignment after inflation

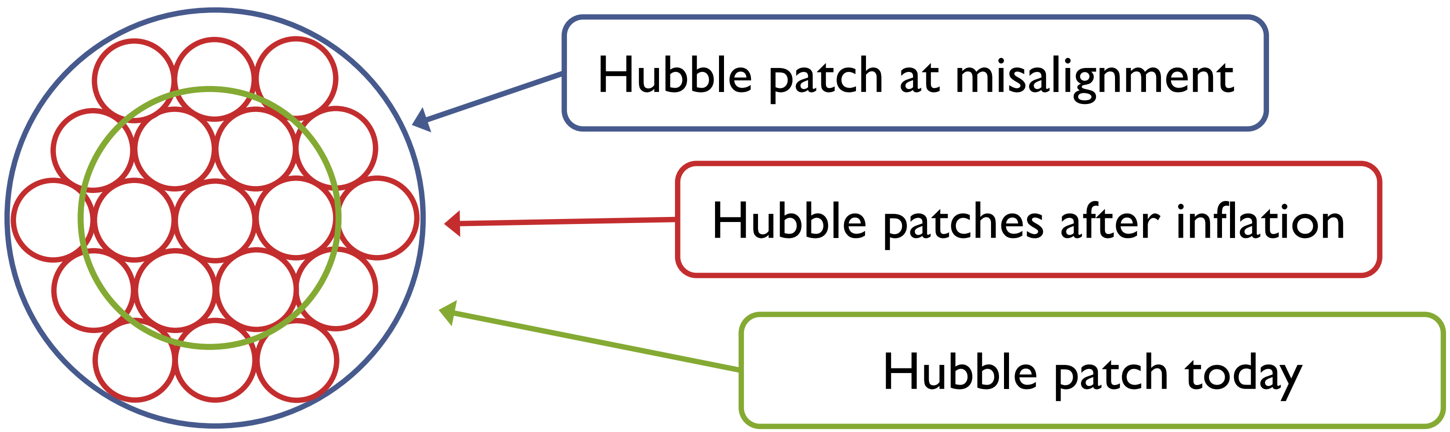
Misalignment before inflation



Misalignment before inflation



Misalignment before inflation



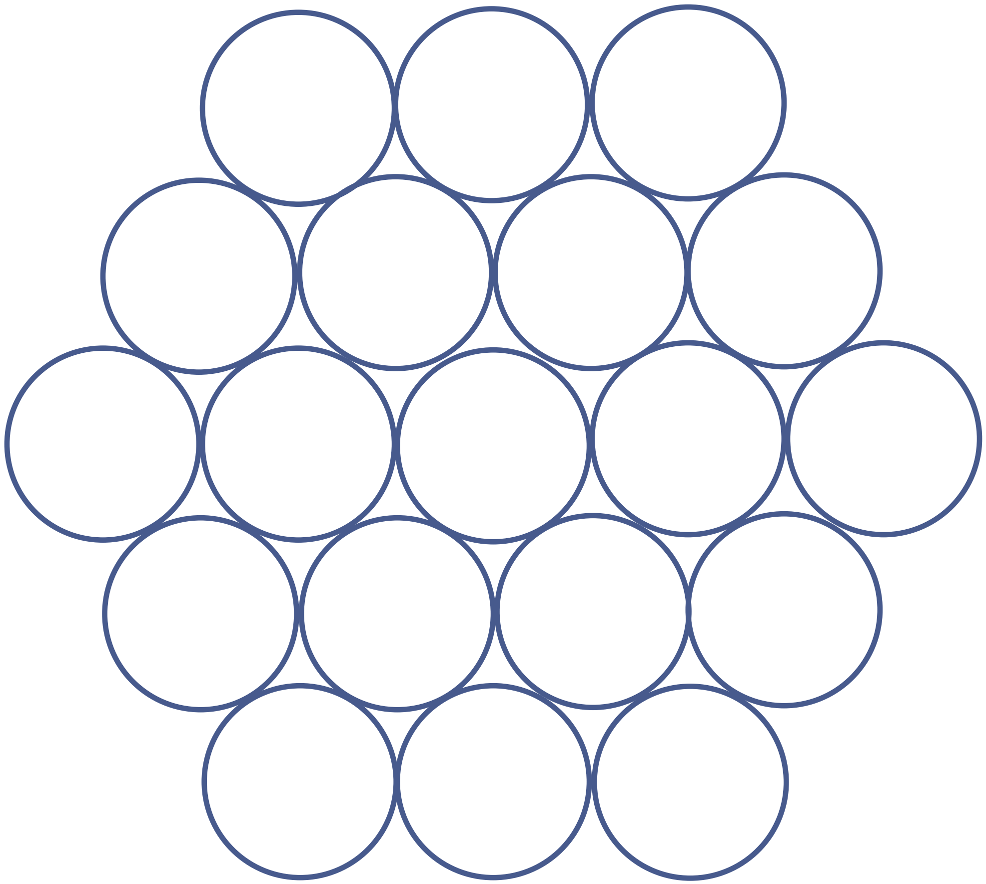
- The Hubble patch today has the same θ_i value
- No isocurvature perturbations
- Same as the CDM case: Needs a cooling process, but axions do not have such processes

Two axion DM scenarios:

Misalignment before inflation

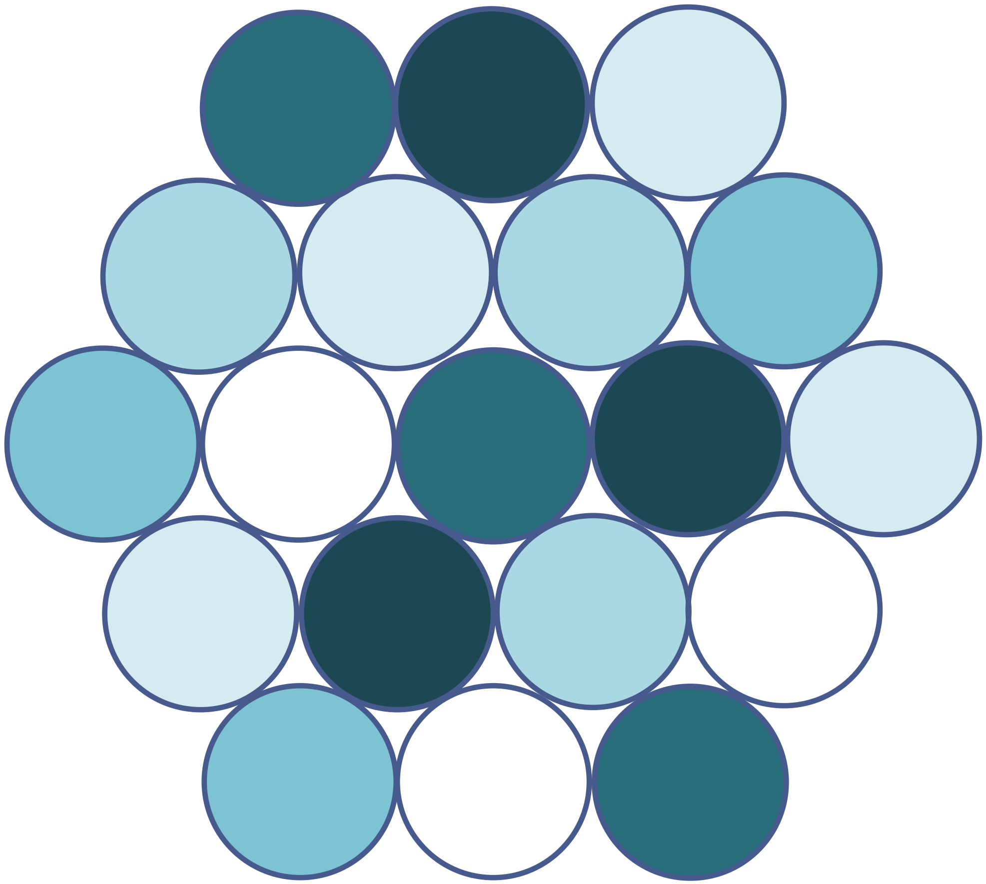
Misalignment after inflation

Misalignment after inflation



- Different Hubble patches after inflation

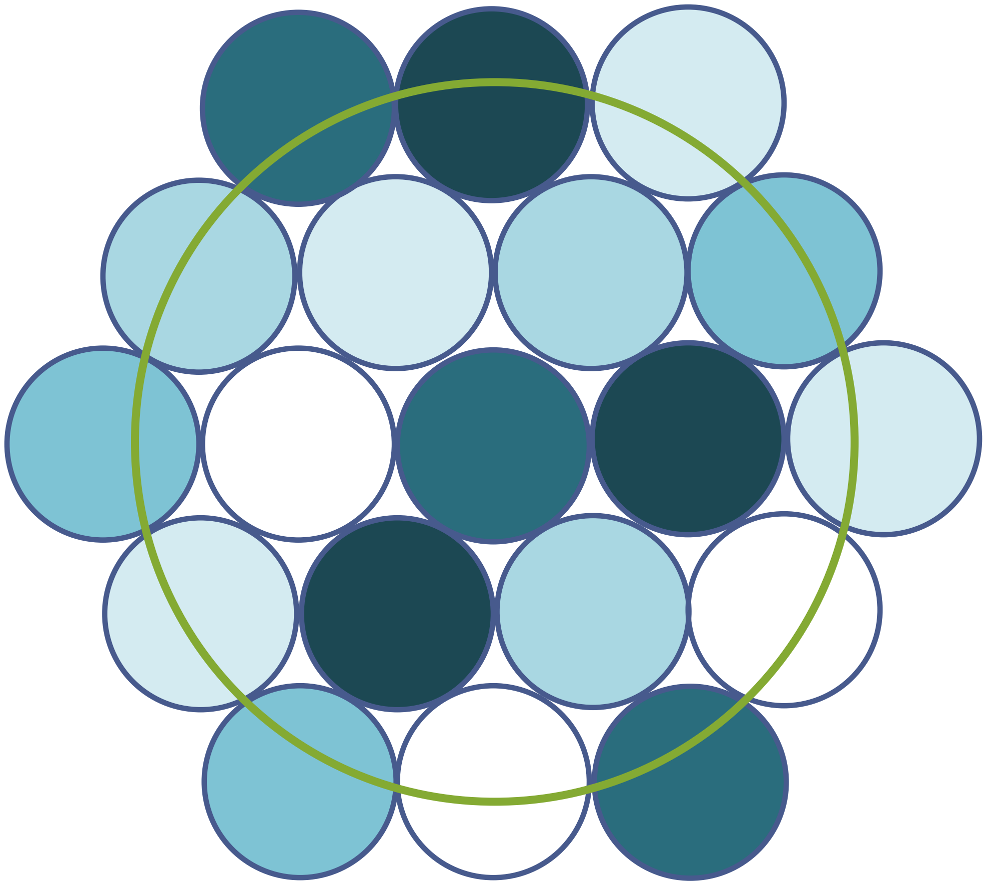
Misalignment after inflation



- 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



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

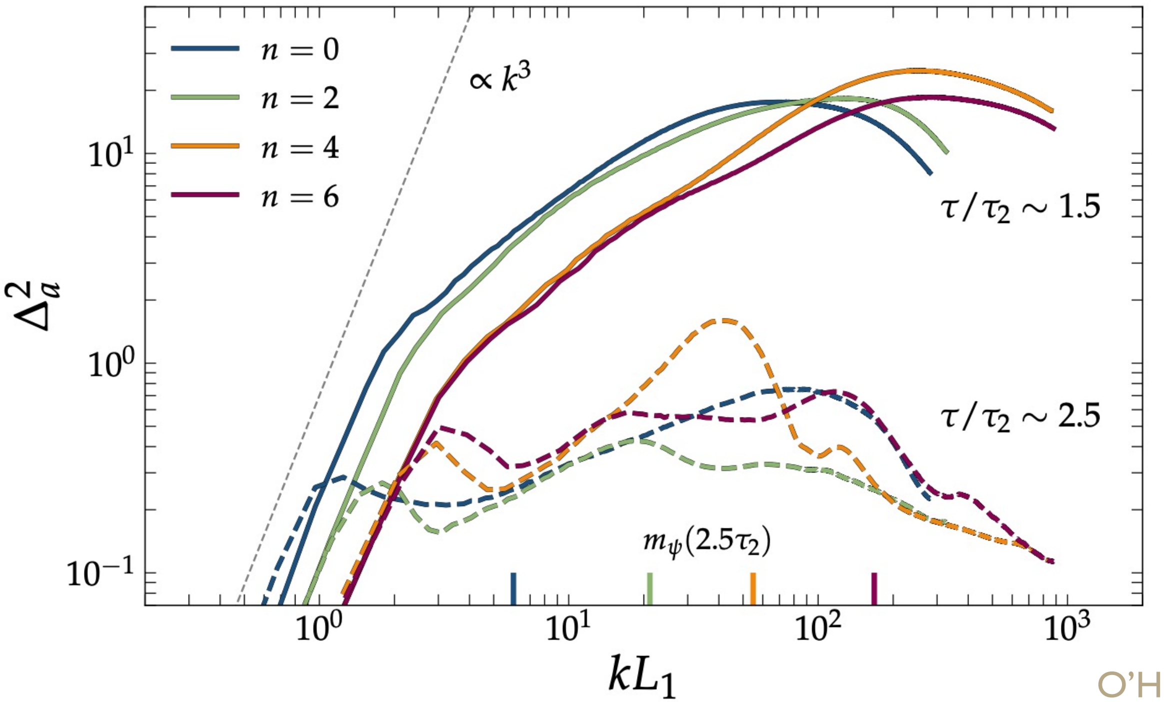
$$\theta_i \in (-\pi, \pi)$$

- Axions can have large isocurvature perturbations at small scales

White-noise spectrum

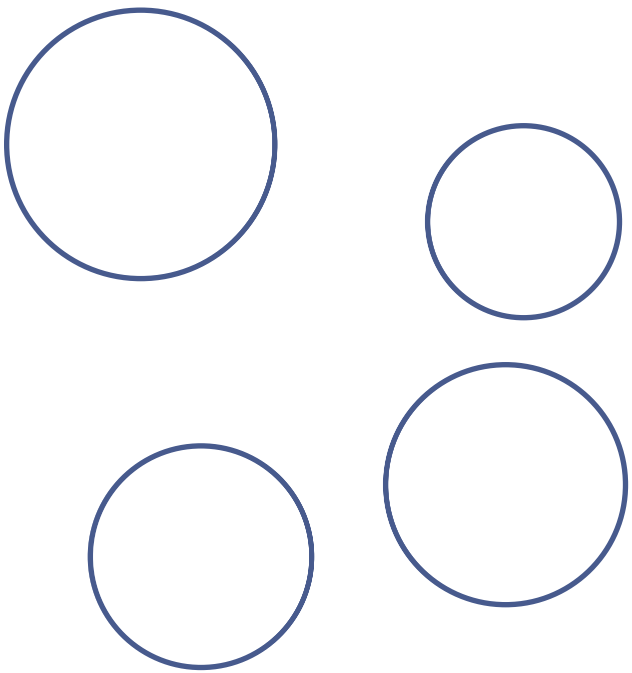
- Misalignment after inflation yields a white-noise density spectrum, which has a flat power spectrum

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



O'Hare et al, 2112.05117

Axion minihalos



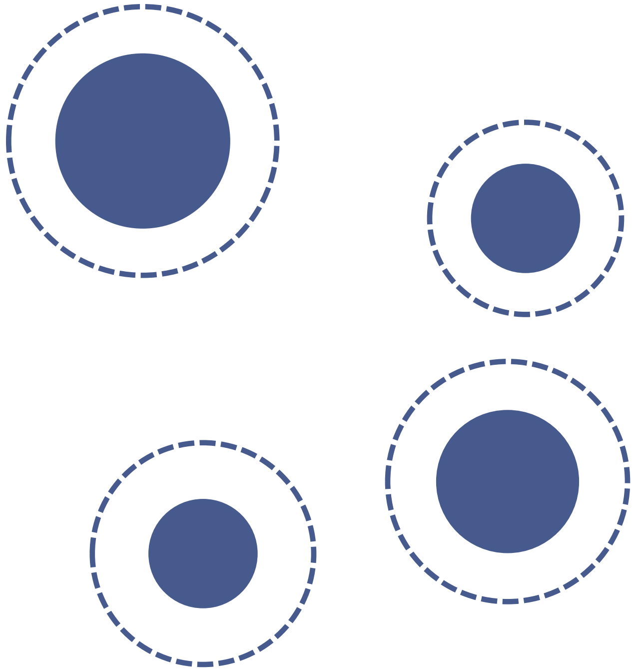
- Axion minihalo (minicluster) forms from the large perturbations at early times

- Such minihalos are already light:

$$M_{h,c} = \frac{4\pi}{3} A_0 \left(\frac{1}{k_0}\right)^3 \bar{\rho}_{a,0}$$
$$\sim 10^{-14}\, M_\odot \left(\frac{\mu\mathrm{eV}}{m_a}\right)^{3/2}$$

- 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 for fragmentation, so no need for a cooling process

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

Goal of this Talk

Axion star mass function

semi-analytic, white-noise part

Constraints

UFD Heating

Ultralight ALP

$(10^{-20} - 10^{-16}$ eV)

Signals

Axion Star Echo

QCD axion and ALP

$(10^{-7} - 10^{-3}$ eV)

MASS FUNCTIONS

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 $t_{ff} \sim t_{eq} \sim \frac{1}{\sqrt{G\rho_{\mathrm{DM}}}}$

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

To get the axion star mass analytically

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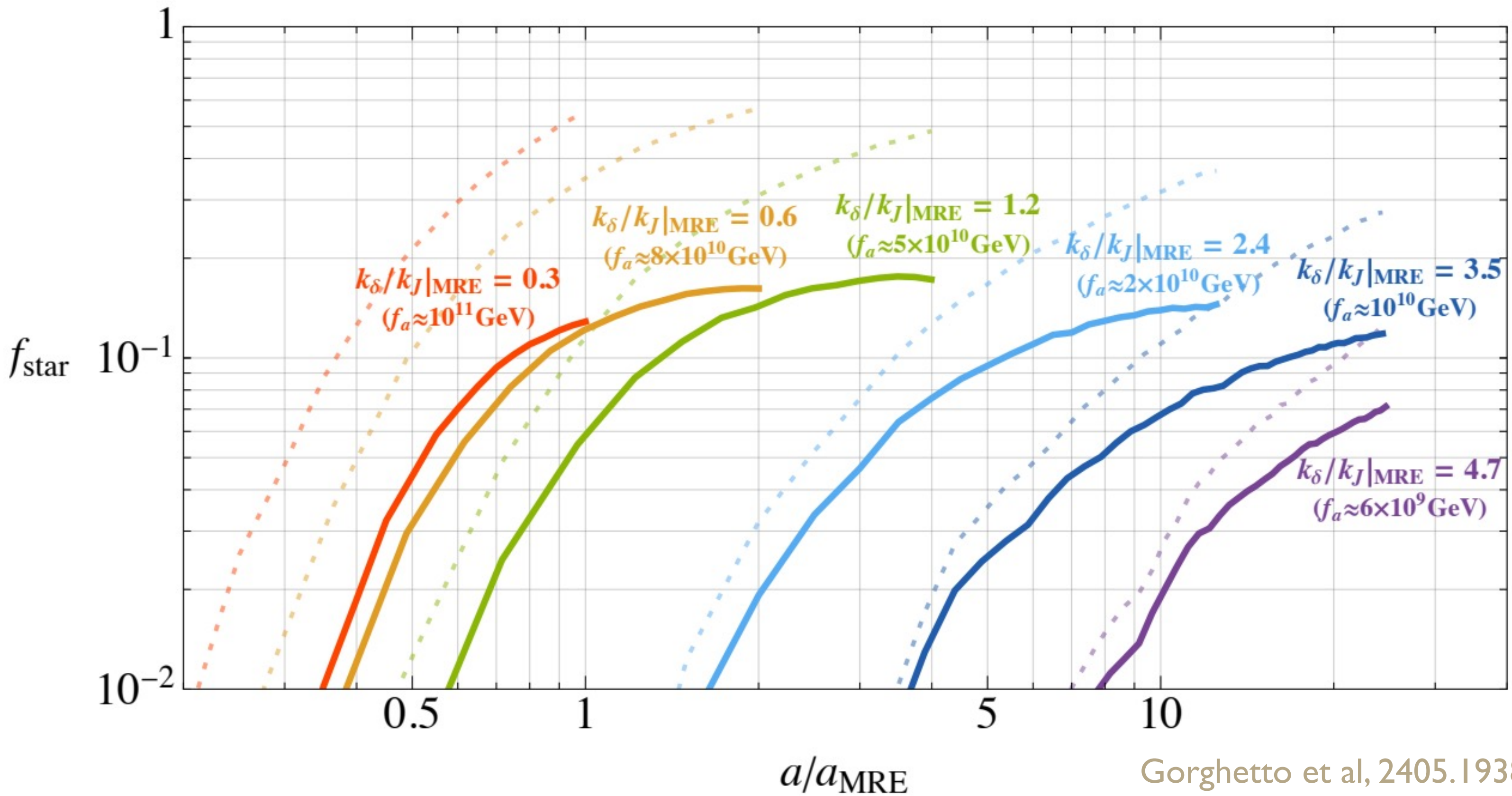


Gorghetto et al, 2405.19389

Axion star mass function

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

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

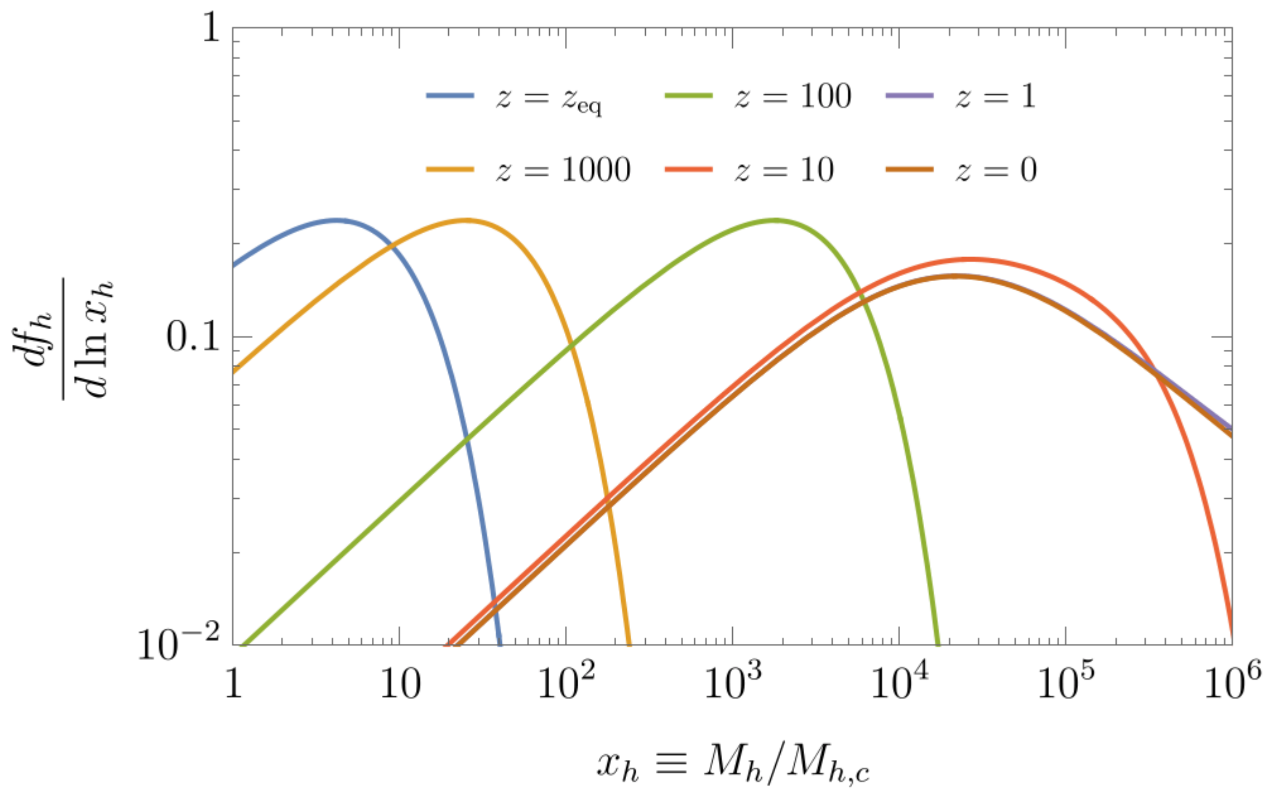
Axion star mass function

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

- $f_\star = \rho_\star / \rho_{\mathrm{DM}}$ and $f_h = \rho_h / \rho_{\mathrm{DM}}$: 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 calculate the mass function of axion minihalos by using the Press-Schechter formalism



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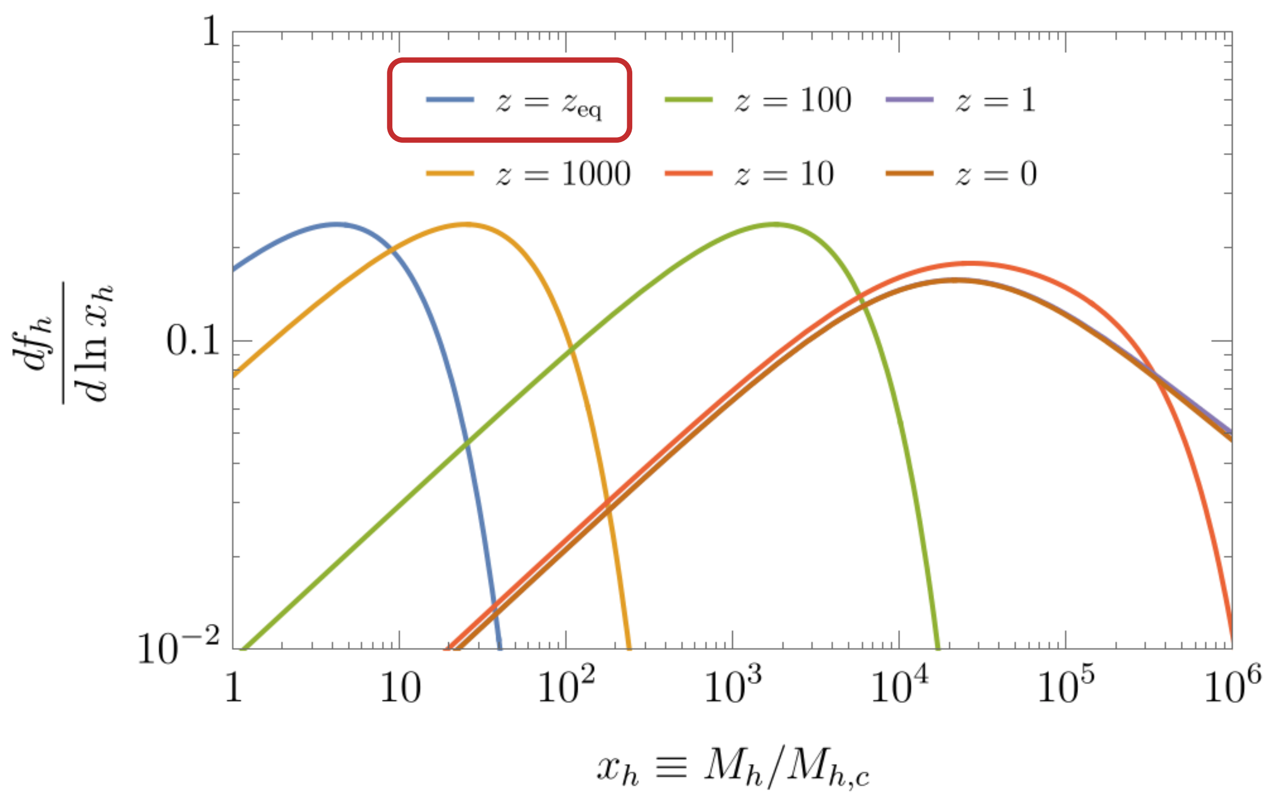


We choose the minihalo mass function at $z = z_{\rm eq}$

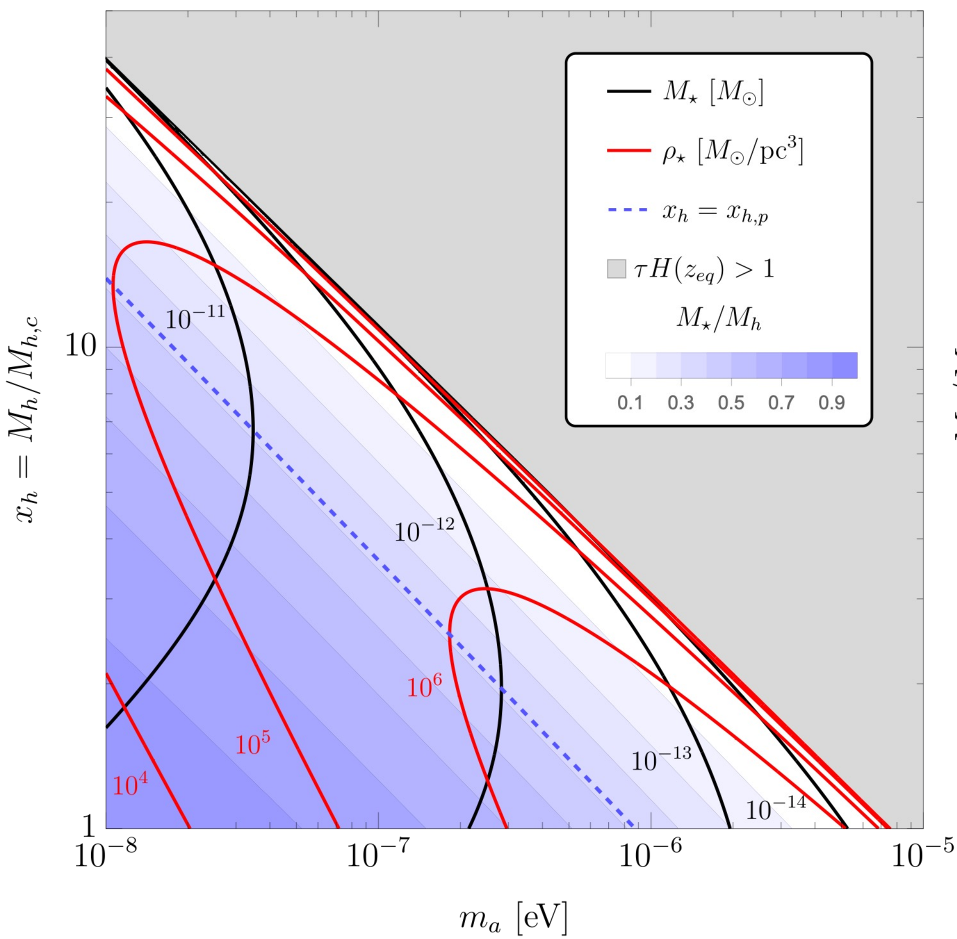
Axion star mass function

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

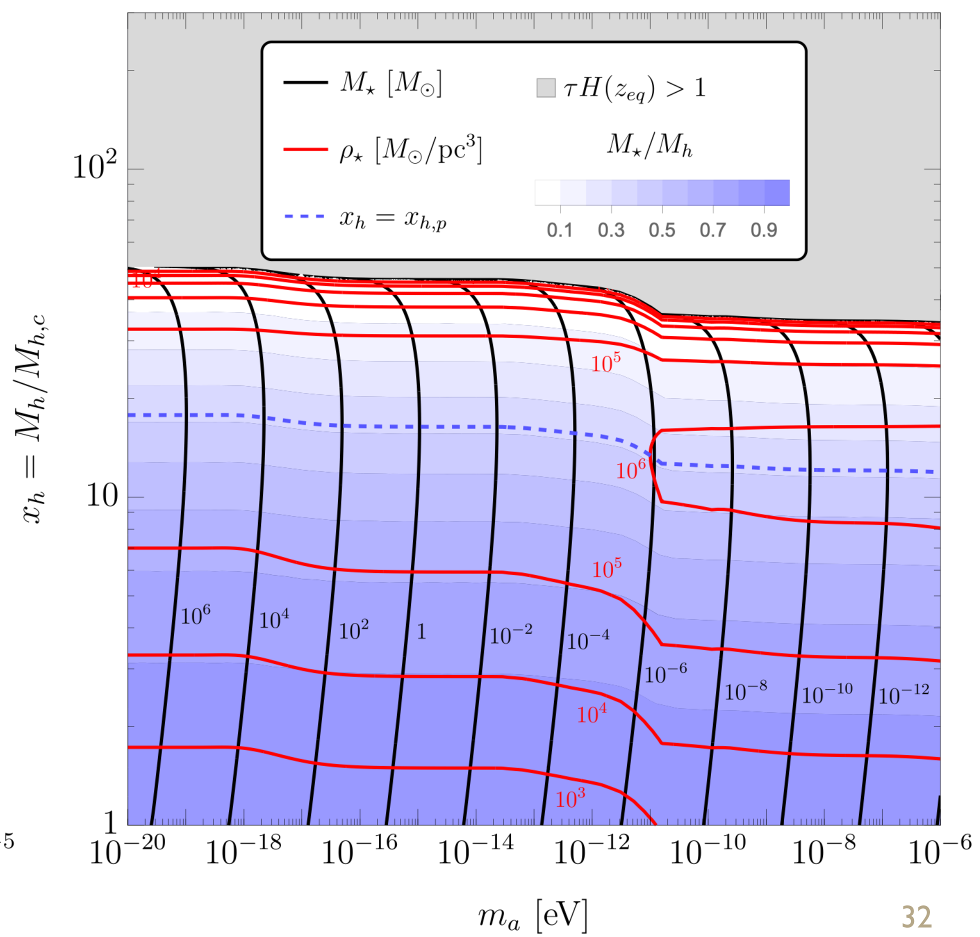
- $f_\star = \rho_\star/\rho_{\rm DM}$ and $f_h = \rho_h/\rho_{\rm DM}$: mass densities
- $\frac{df_h}{dM_h}$ is the mass distribution of axion minihalos
- $\frac{dM_h}{dM_\star}$ can be obtained from $M_\star$ as a function of M_h

Axion star in minihalos

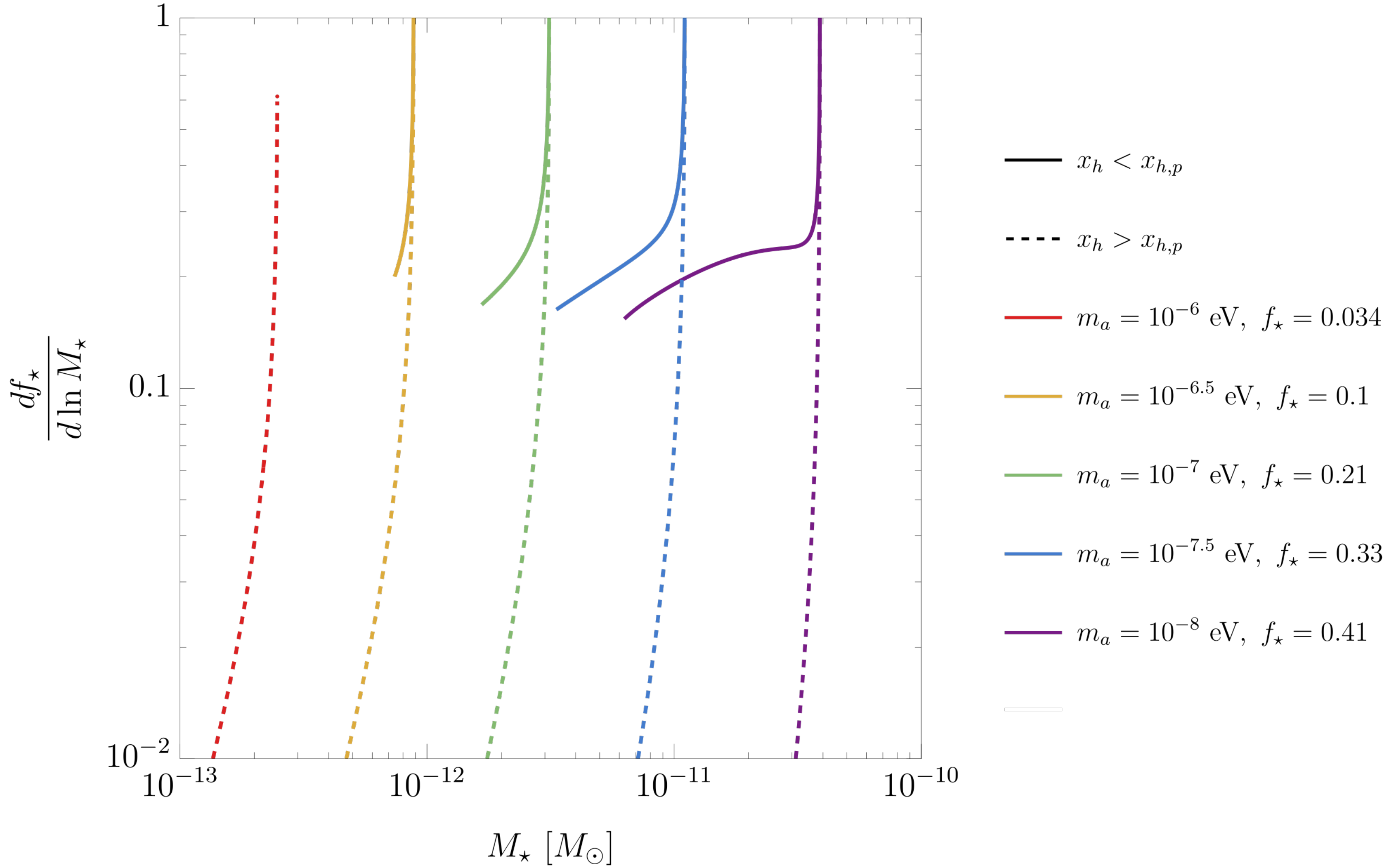
QCD Axion



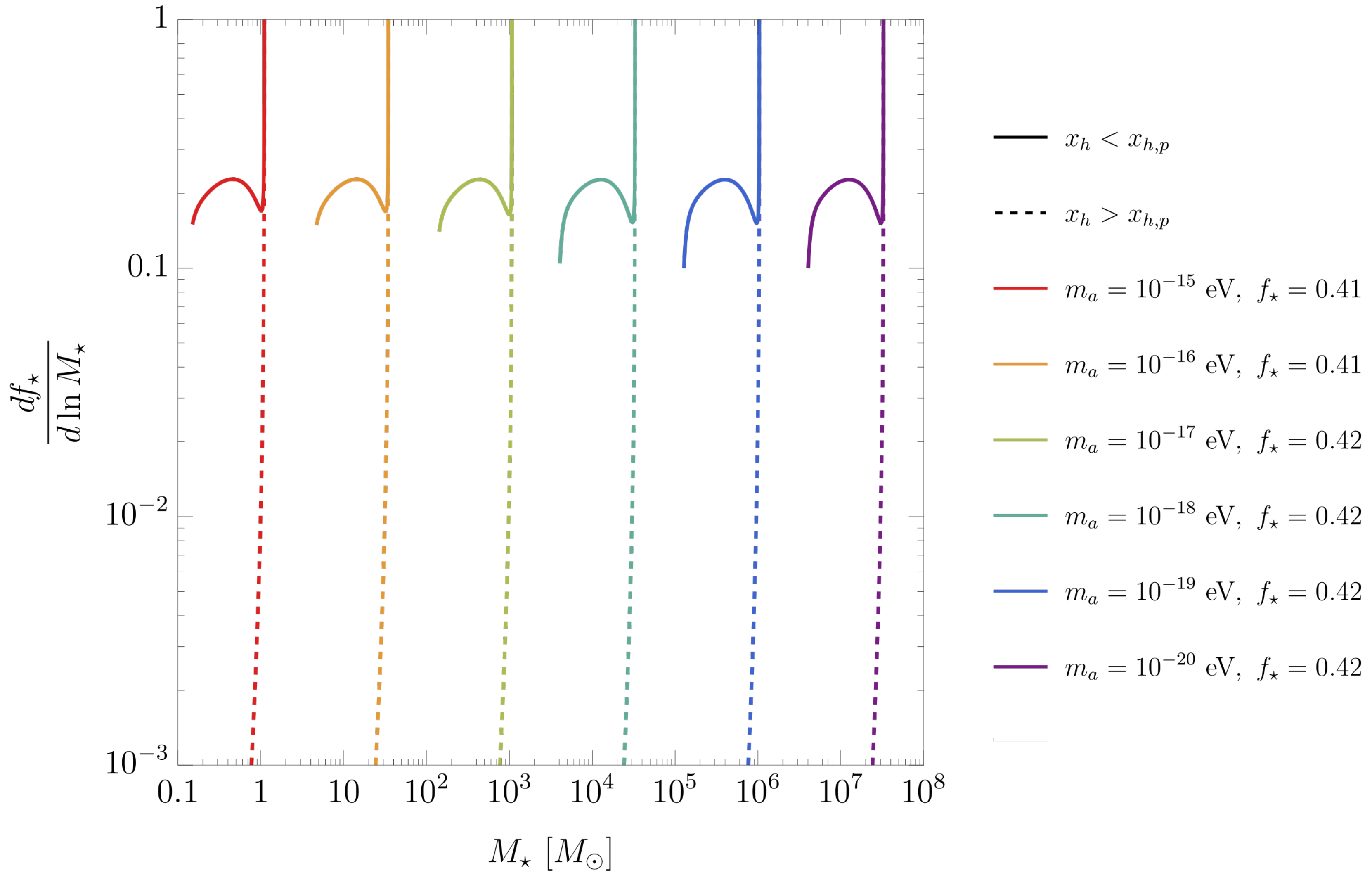
ALP



Axion star mass functions (QCD axion)



Axion star mass functions (ALP)



CONSTRAINTS

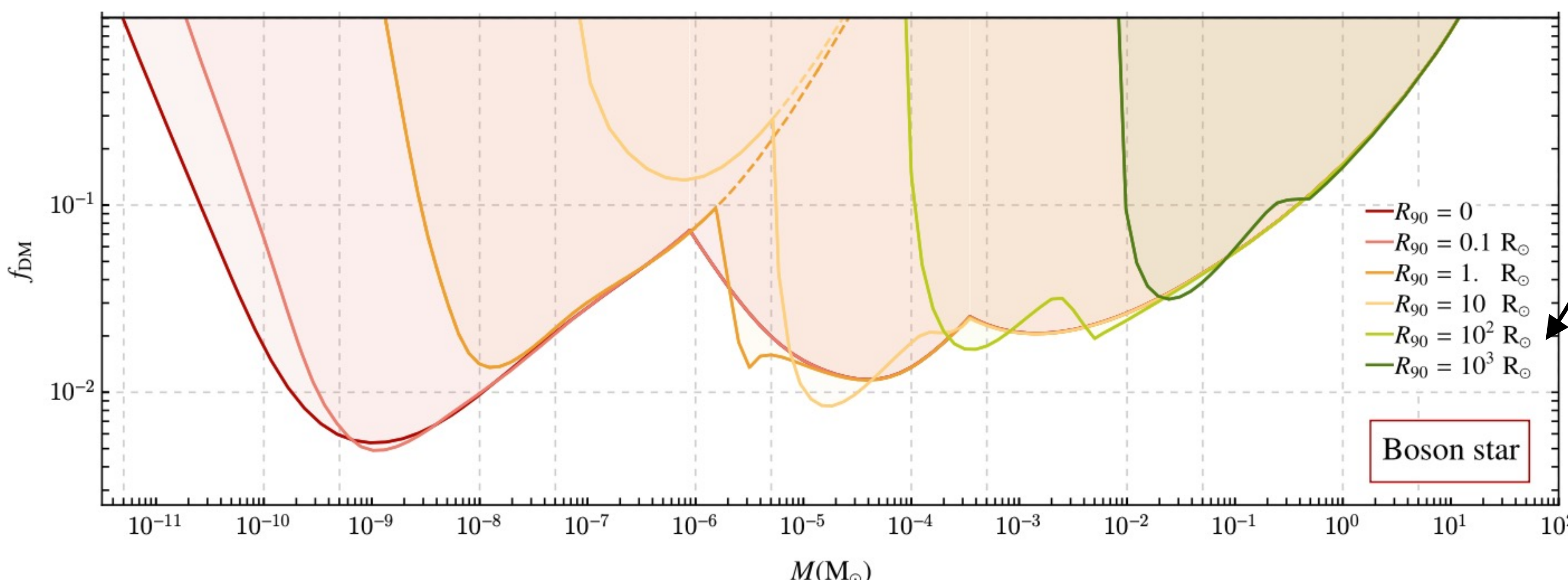
QCD axion stars

- 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 this 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 $R = 10^2\ R_\odot$



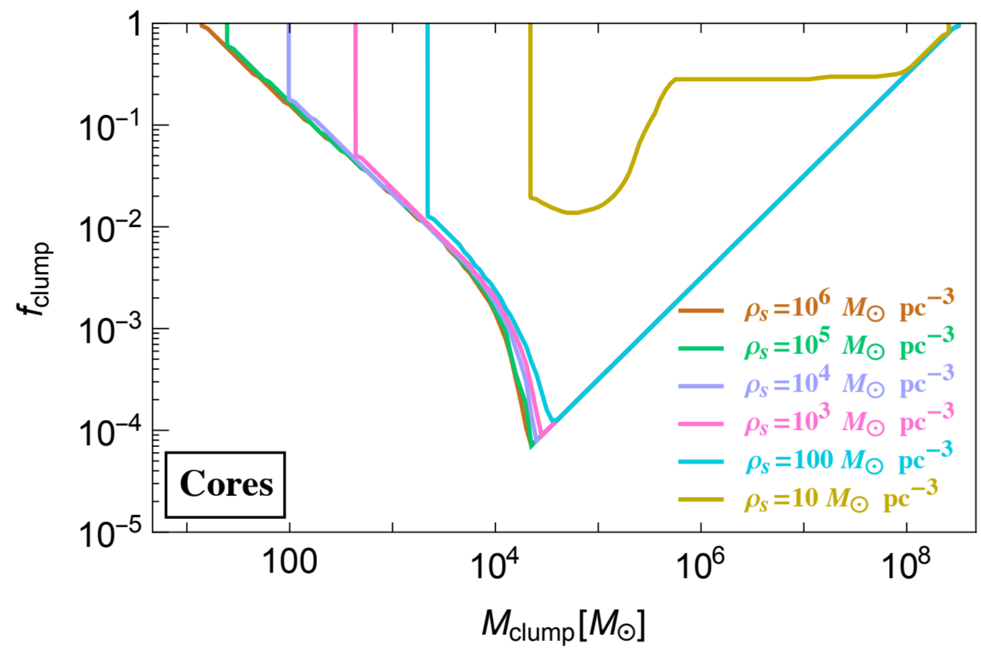
Croon et al, 2007.12697

ALP stars

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

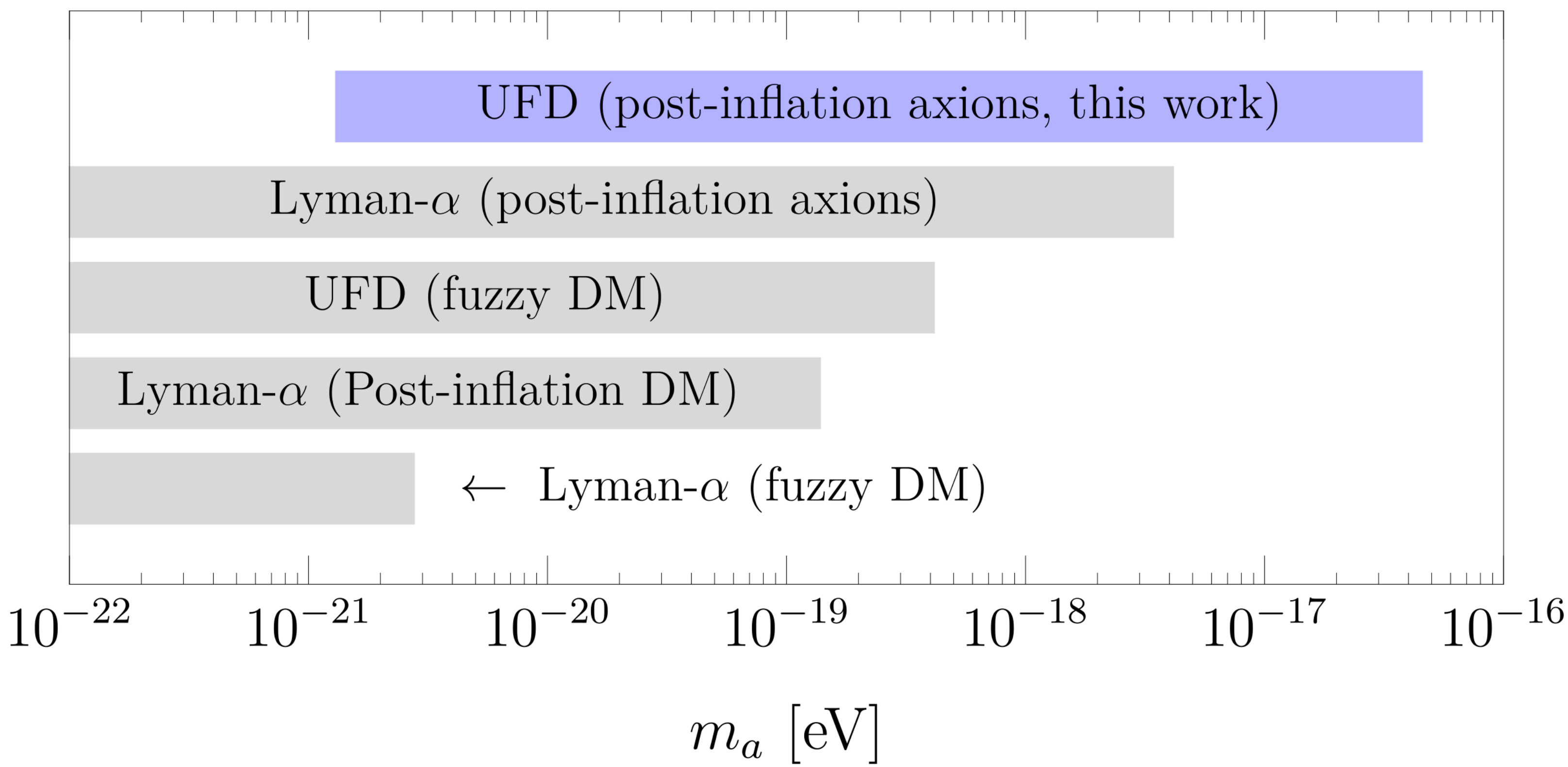
- The best way to detect this mass range is heating of ultra-faint dwarfs (UFD)

Graham and Ramani, 2311.07654, 2404.01378



ALP mass constraints

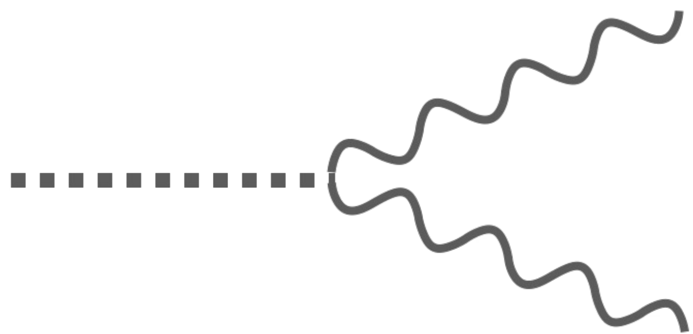
$$\int f_{\rm UFD}^{-1}(M_\star, \rho_\star)\,\frac{df_\star}{dM_\star}\,dM_\star < 1$$



SIGNALS

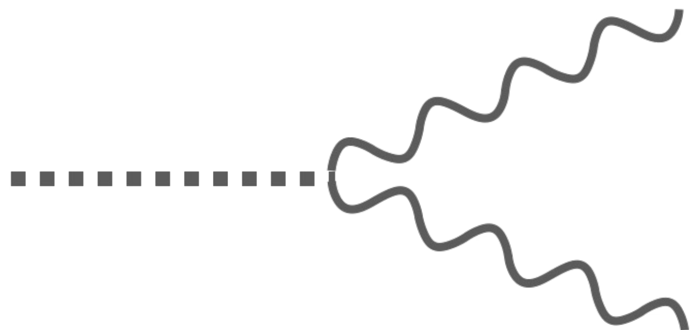
Yitian Sun (Postdoc at McGill University)

Axion-photon Coupling



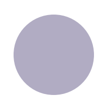
$$\mathcal{L} \supset -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu} = g_{a\gamma\gamma}\, a\,(\vec{E}\cdot\vec{B})$$

Axion Decay

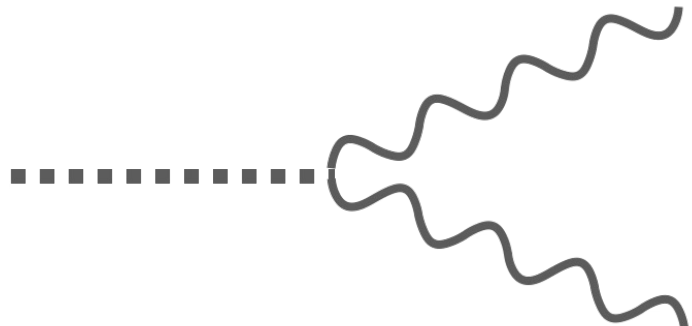


$$\mathcal{L} \supset -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu} = g_{a\gamma\gamma}\, a\,(\vec{E}\cdot\vec{B})$$

m_a



Axion Decay

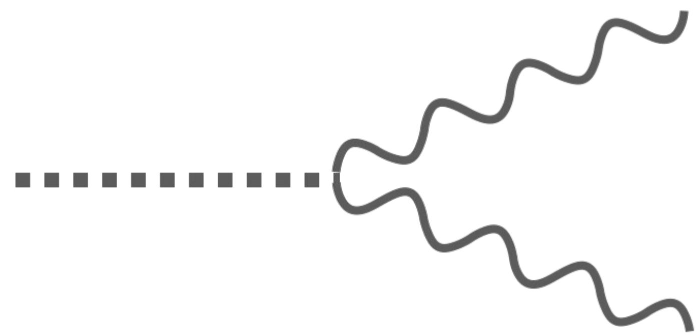


$$\mathcal{L} \supset -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu} = g_{a\gamma\gamma}\, a\,(\vec{E}\cdot\vec{B})$$

$$\omega = m_a/2$$

$$\tau_a = \frac{1}{\Gamma_a} = \frac{64\pi}{m_a^3\, g_{a\gamma\gamma}^2} \sim 4\times 10^{35}\,\mathrm{yr}\left(\frac{m_a}{\mu\mathrm{eV}}\right)^{-3}\left(\frac{g_{a\gamma\gamma}}{10^{-10}\,\mathrm{GeV}^{-1}}\right)^{-2}$$

Axion Stimulated Decay



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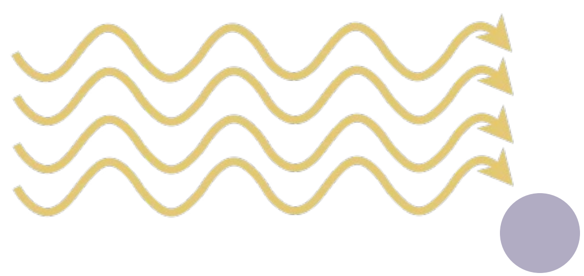
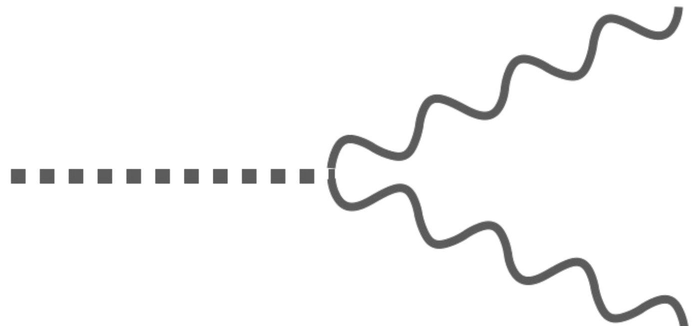
$\omega = m_a/2$

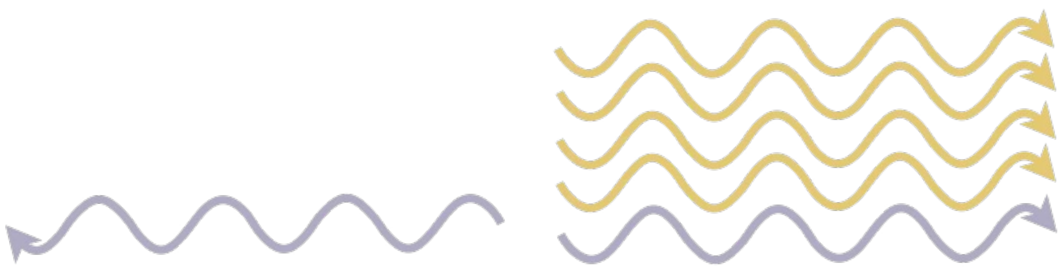


Axion Stimulated Decay



$$\mathcal{L} \supset -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu} = g_{a\gamma\gamma}\, a\,(\vec{E}\cdot\vec{B})$$

"Axion Echo"
"Gegenschein"

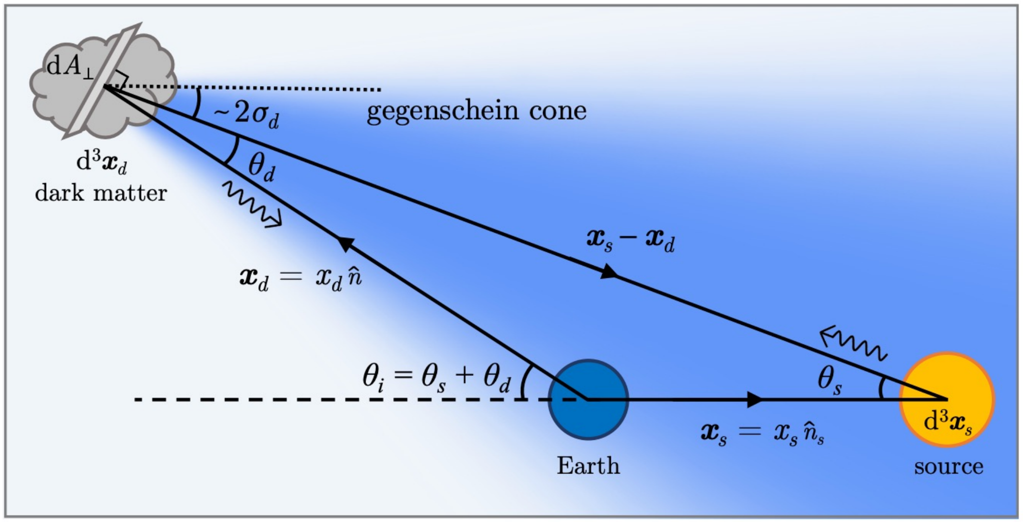


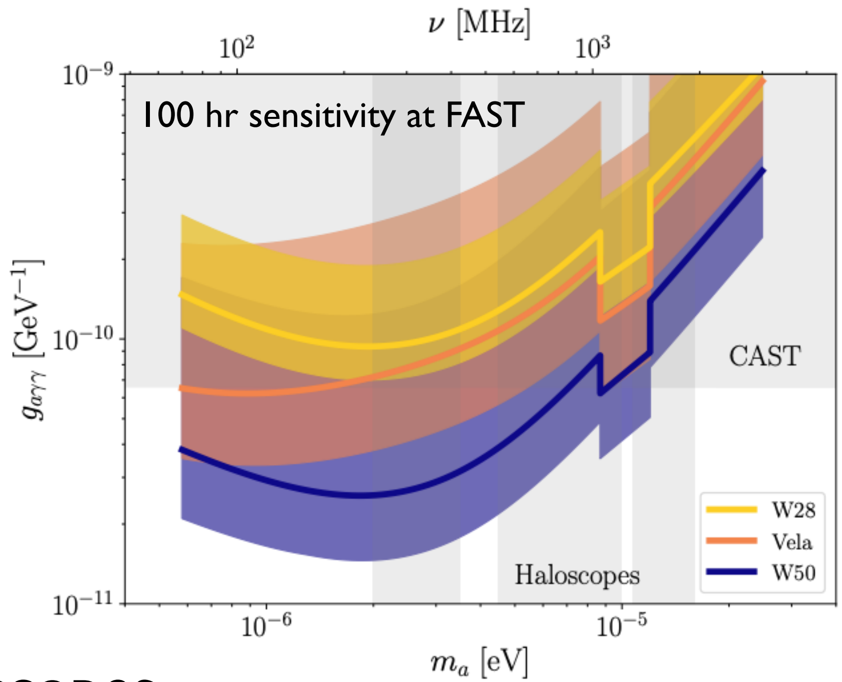
$$\omega = m_a/2$$

$$\frac{d\Gamma_{\text{echo}}}{d\Omega} = (1+f_\gamma)\frac{\Gamma_a}{4\pi}$$

Arza and Sikivie, 1902.00114

Axion Halo Echo

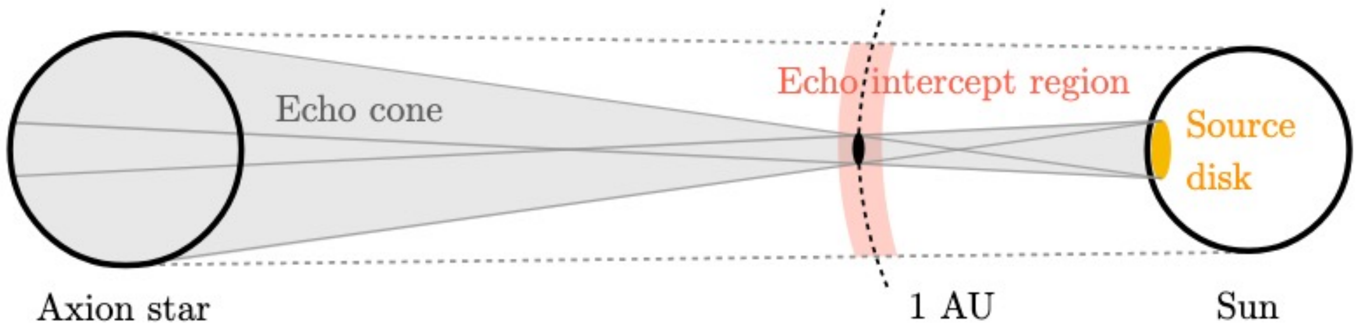




- Can probe axion DM in radio telescopes
- Typical sources for axion halo echo are supernova remnants
- Brighter nearby sources (e.g. the Sun) cannot be used due to blurring from DM velocity dispersion ($\sigma_v \sim 10^{-3}$)

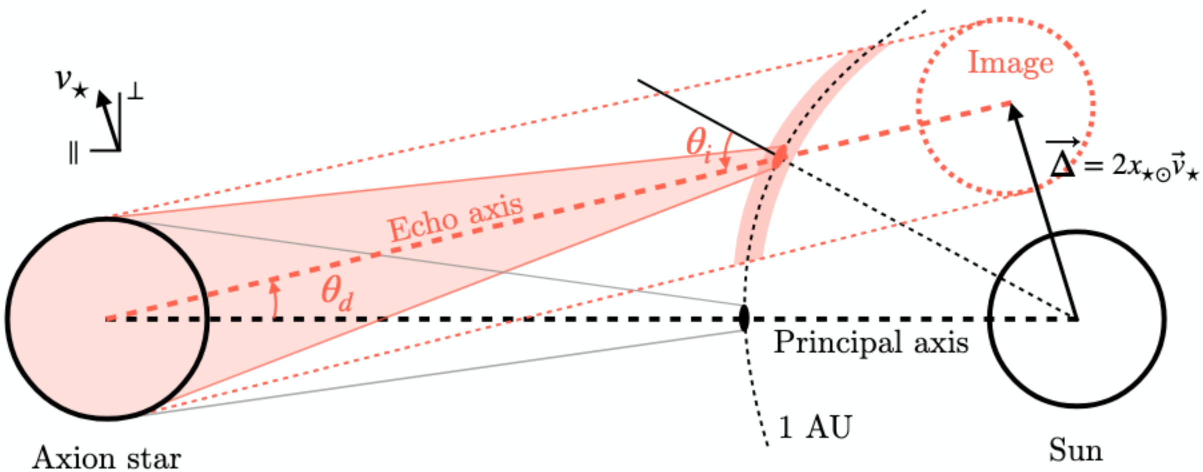
Sun et al, 2110.13920
Buen-Abad et al, 2110.13916

Axion Star Echo



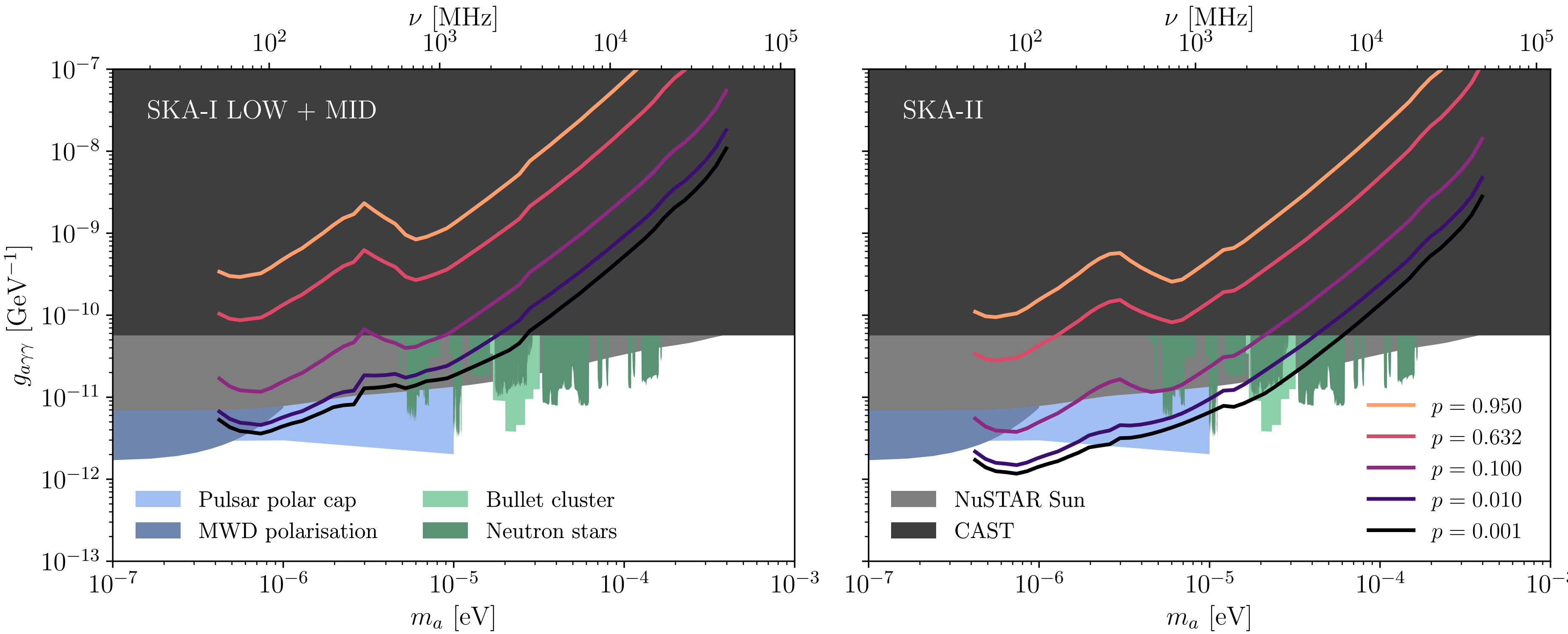
- Axions in axion stars are coherent ($\sigma_v \sim 10^{-9}$)
- We can use the brightest radio source, the Sun
- $$S_e \approx \frac{g_{a\gamma\gamma}^2}{16}\frac{\overline{I_{s,\nu}}M_\star}{x_\star^2}$$
  $$\approx 27\ \mu\text{Jy kHz}\left(\frac{g_{a\gamma\gamma}}{10^{-12}\ \text{GeV}^{-1}}\right)^2\left(\frac{M_\star}{10^{-12}\ M_\odot}\right)\left(\frac{x_\star}{100\ \text{AU}}\right)^{-2}$$

Geometry of Axion Star Echo



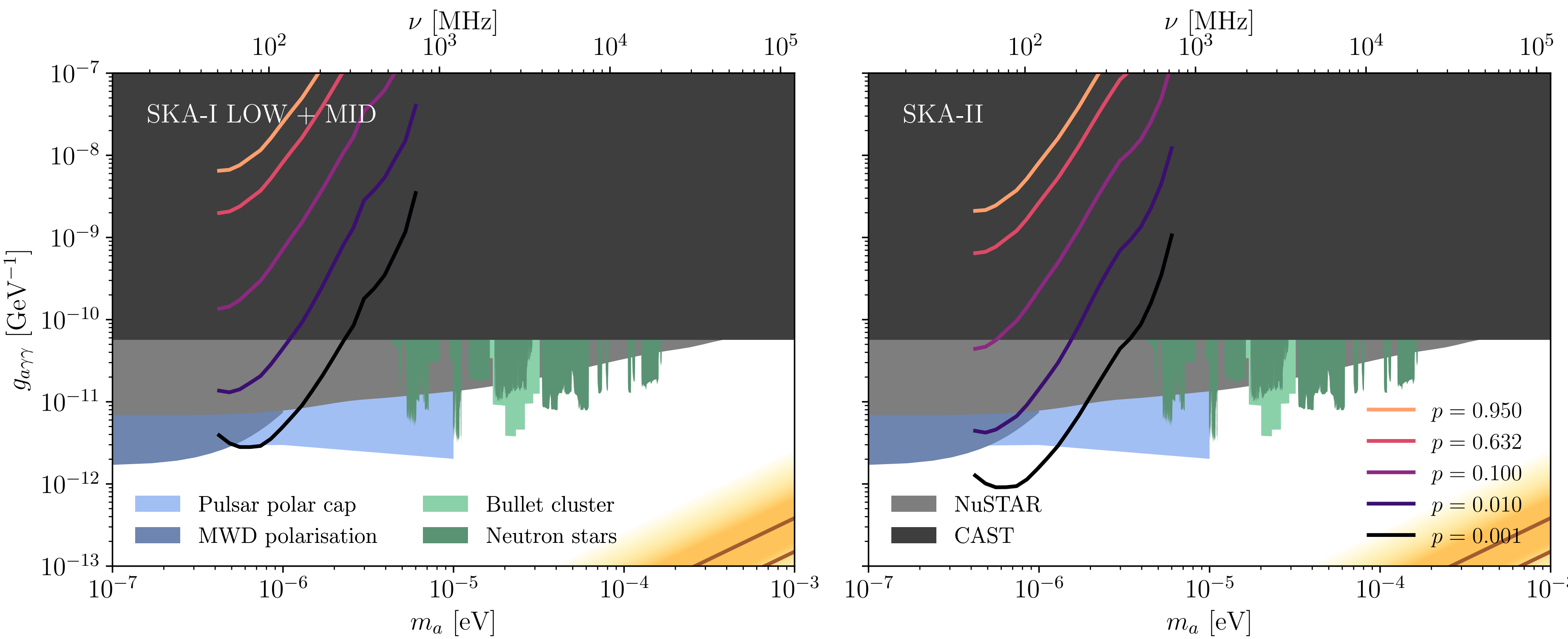
- Motion of axion stars tilts the echo
  - ➤ The displaced patch must still cross Earth's orbit
  - ➤ $x_\star \lesssim 10^3$ AU
- Typical Earth crossing time ~ 10 hours
  - ➤ A distinctive transient
- Dispersion, Earth's shadow, self-stimulation, …
  - ➤ all under control

Preliminary ALP Sensitivity



- Signal is dominated by the closest axion star
- $n_\star \sim 10^{-5}\mathrm{AU}^{-3}$, but $\Omega_{\mathrm{obs}}/4\pi \sim 10^{-5}$ so we need to be lucky
- p is probability that the nearest axion star is close enough
  - ➤ $p = 0.001$ lucky discovery, $p = 0.95$ exclusion

Preliminary QCD axion Sensitivity



SUMMARY

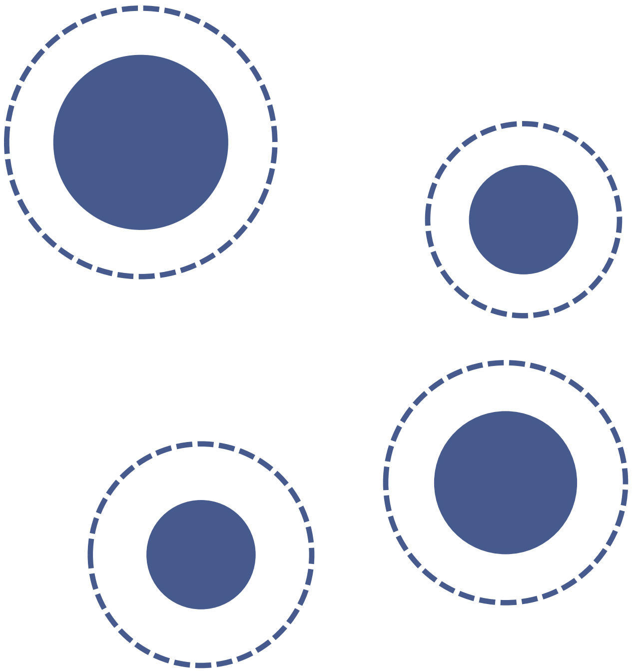
Summary

- We calculate axion star mass functions semi-analytically
- The resulting mass function gives constraints on axion masses from heating of ultra-faint dwarf galaxies
- Nearby axion stars may echo the Sun, giving a radio signal within SKA reach in a lucky case

THANK YOU

BACK UP

Axion stars

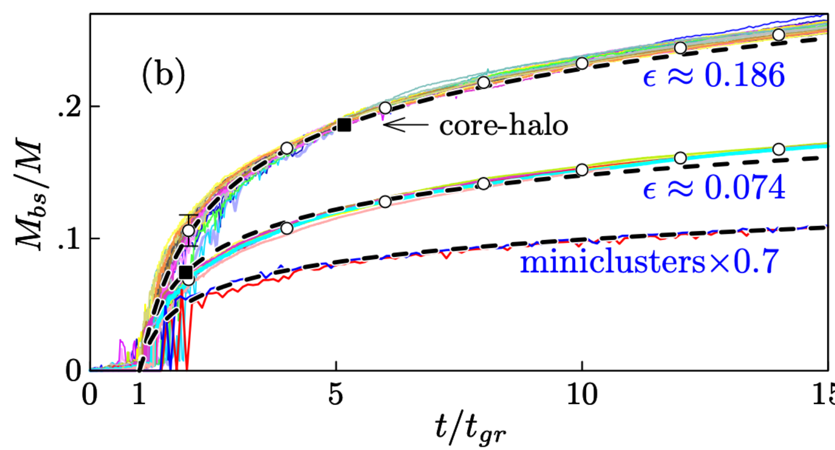


- Axion star mass in a given halo mass M_h after time t is

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

- $x_\star(t)$ is the axion star evolution function depending on m_a and M_h

- $x_\star(\tau_{\mathrm{gr}}) = 0$ and $x_\star(\infty) = 1$



Dmitriev et al, 2305.01005

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