UNIVERSITY of WASHINGTON

Axion Dark Matter in the Sky

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H. Xiao, I. Williams, M. McQuinn, Phys. Rev. D 104, 023515 (2021)
A.E. Nelson and H. Xiao, Phys. Rev. D 98 (2018) 063516
V. Iršič, H. Xiao, and M. McQuinn, Phys. Rev. D 101, 123518 (2020)
Ongoing work with P. Fox and N. Weiner

Berkeley Cosmology Seminar

Storyline

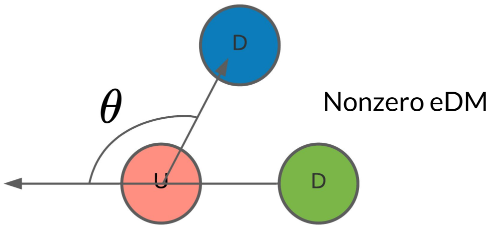
- Why is the axion an interesting dark matter candidate?
- Substructure formation from axion perturbations
- Detectability of axion minihalos
- The axion universe

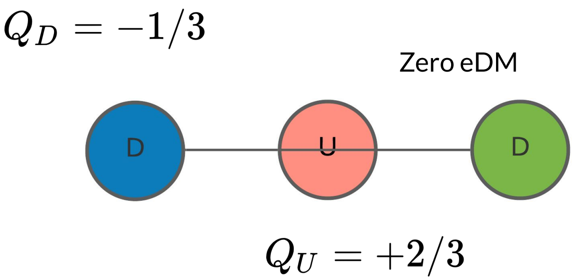
Theoretical motivation of the axion dark matter

Why is axion interesting?

A natural **solution** to the so-called **strong CP problem! (C- Charge, P-Mirror)**

Why the **CP symmetry** is conserved in strong interaction**?** The neutron electric dipole moment (eDM) provides a direct measure of the **CP violation**. Think about the classical eDM:





From the measurements of the neutron eDM: $\theta < 10^{-10}$. This small number is mysterious. The anthropic solution is **not** likely unlike other fine-tuning problems.

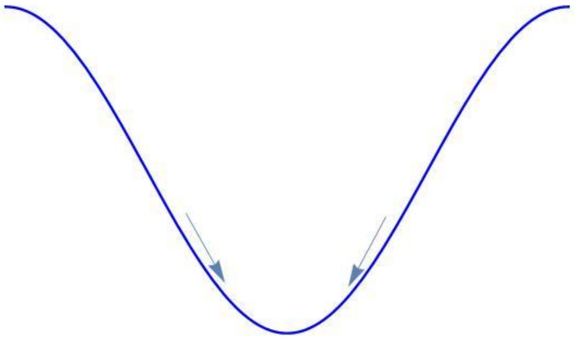
The axion solution

A dynamical θ angle. $\theta = 0$ is simply the **ground state!**

At quantum level, no geometric angle anymore. The θ parameter in field space is still the measure!

Promote this parameter to a **dynamical field!** Potential arises from the strong interaction. (R. D. Peccei and H. R. Quinn, 1977)

Two parameters in this theory: symmetry breaking scale f_a and axion mass m_a. (They are related if strong interaction is responsible for the potential)



$V(\theta) \propto (1 - \cos\theta)$

Axion Dark Matter

Potential turned on by strong interaction

$\Downarrow$

Non-zero vacuum energy

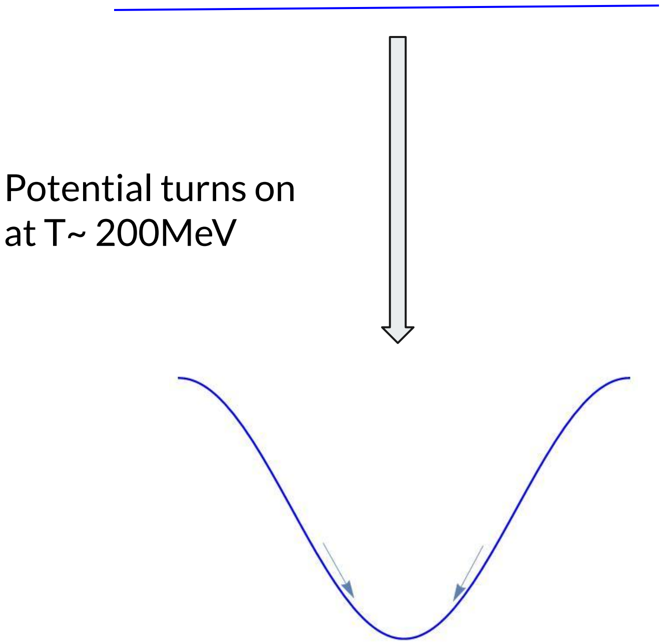
$\Downarrow$

Convert to matter density

This is called **vacuum misalignment mechanism.**

To produce the correct dark matter relic abundance, axion mass is

$m_a \sim 10^{-5}\mathrm{eV}$

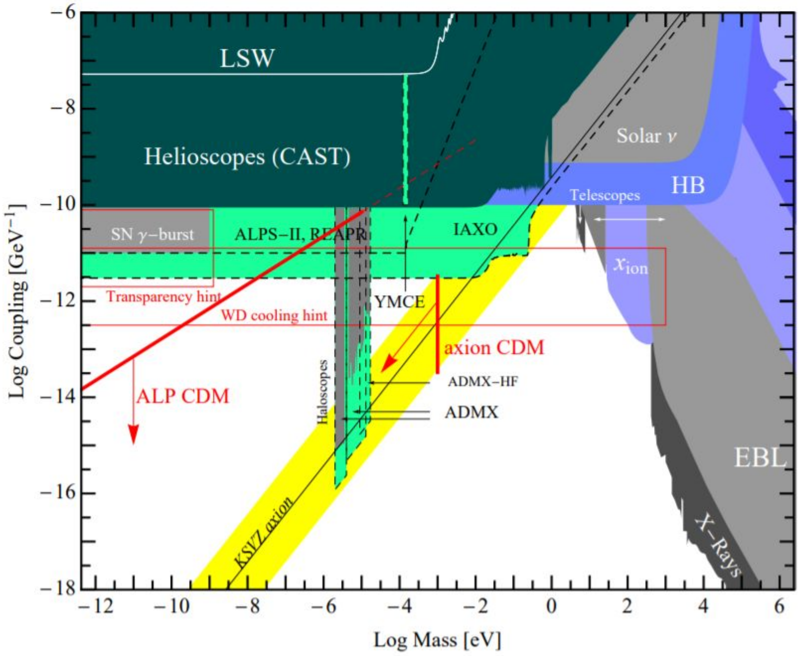


Current Bounds

Yellow: **QCD axion parameter space**

Grey: Constraints from astronomical observations

Dark Green: experimentally excluded regions



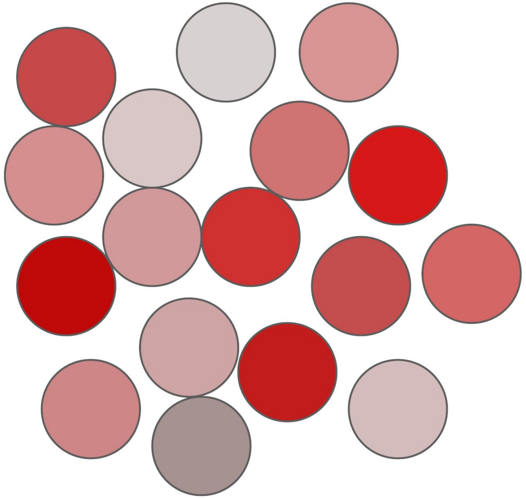
Ringwald, 2012

Axion miniclusters

Substructure formation from axion perturbations

Symmetry breaking happens, **uncorrelated** field values at different horizon patches. $\theta \in (-\pi, \pi)$

Assumption: **symmetry breaking after inflation**



Look from large scales, they are white!

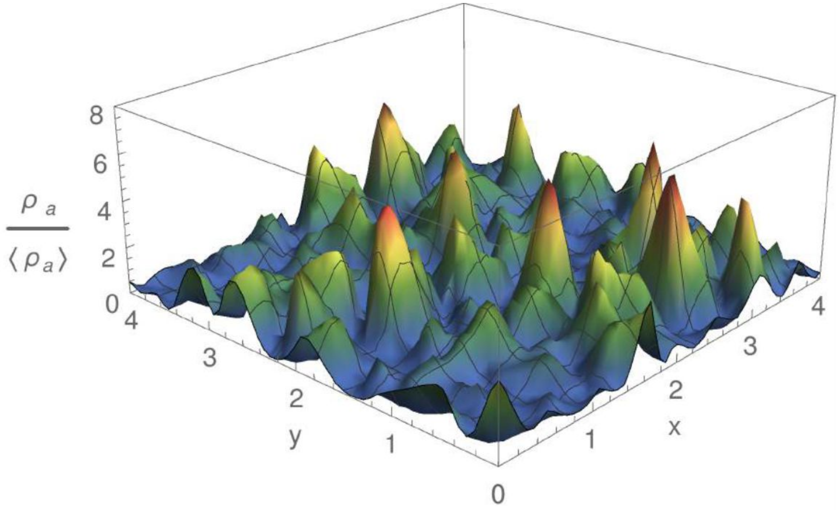
Initial Density Perturbations

Uncorrelated field values

⇓

Order one white-noise matter density fluctuations

Forming miniclusters at matter-radiation equality! (C.J.Hogan, M.J.Rees, 1988)



E. Hardy, 2017

The size of the axion miniclusters

Considering the **QCD axion (**that solves the strong CP problem**)**, the characteristic mass is:

$$M_0 \equiv \frac{4\pi}{3}(\pi L_1)^3 \bar{\rho}_{a,0} = 2.3 \times 10^{-10} \left(\frac{50\mu\mathrm{eV}}{m_a}\right)^{0.51} M_\odot$$

Miniclusters will evolve and merge. We call them axion minihalos at late times.

The inhomogeneity can be well described by a **white-noise power spectrum** because the matter density is randomly distributed and **uncorrelated** in different horizon patches.

Natural Questions from Axion Miniclusters

- Are they detectable? You may think not.
- How do they evolve with time?
- Are there still axion particles that remain unbound? (Important for the direction detection)

We will use N-body simulations to directly study the detectability of axion miniclusters.

Detectability of axion minihalos

New Ideas of Detecting Small Structures

- Pulsar timing arrays (sensitive to masses, $10^{-12} M_\odot - 100 M_\odot$, *J. A. Dror, H. Ramani, T. Trickle, and K. M. Zurek,* 2019)

- Lensing in Highly Magnified Stars (*L. Dai and J. Miralda-Escudé,* 2019)

Those small substructures are **detectable!** Time to study their formation and evolution from interesting physics.

The Square Kilometre Array

James Webb Space Telescope

Simulation Setup

Initialize the particles with the **white-noise power spectrum** and run it with the MP-Gadget.

Simulation box size: **50 pc/h**,

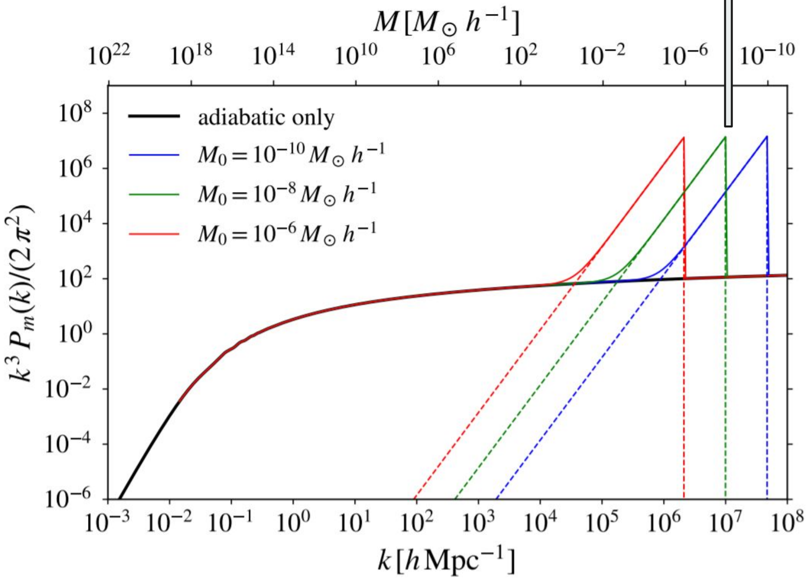
Particle numbers: **1024^3**

Redshifts: z=30,000 to **z=19**.

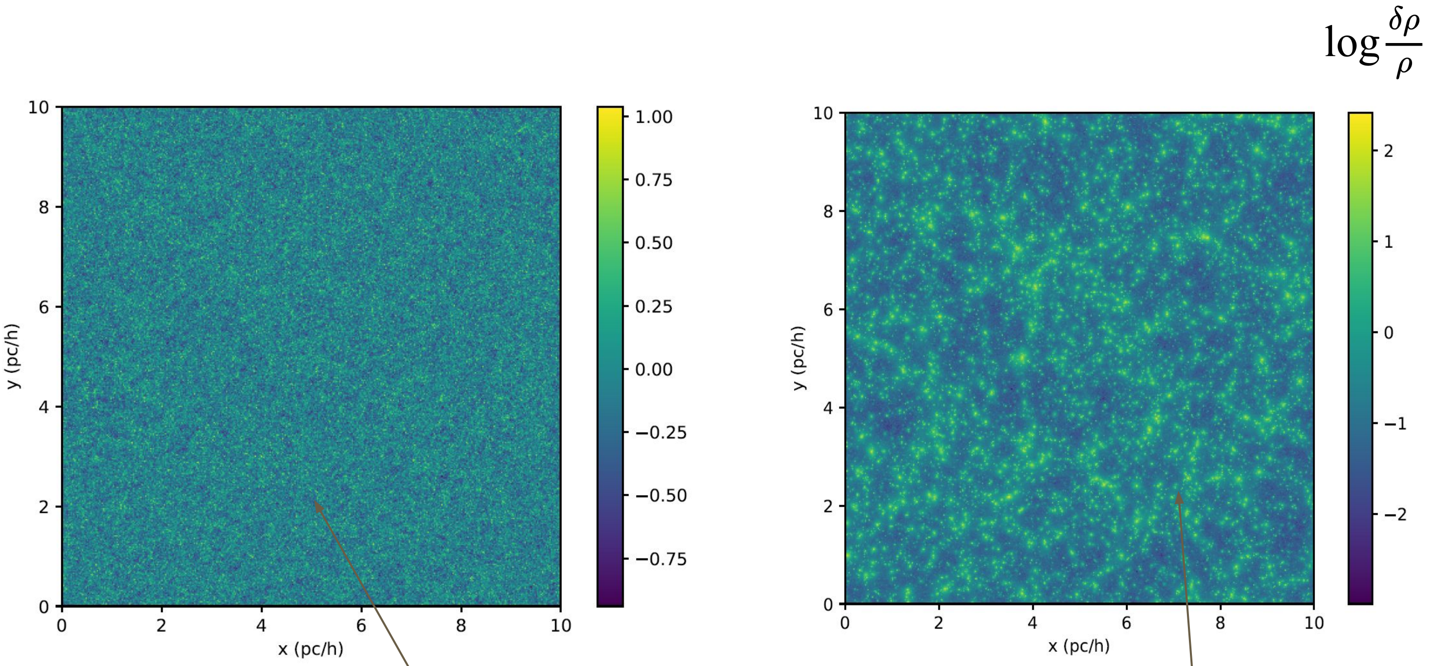
Lowest redshift so far in the literature of simulating axion minihalos. (Will show later why z~19 is sufficient) (H. Xiao, I. Williams, M. McQuinn, 2021)

Scale-free simulation. Can be rescaled to arbitrary masses!

High k dominated by the white-noise power!



L. Dai and J. Miralda-Escudé, 2019



z=99, white noise

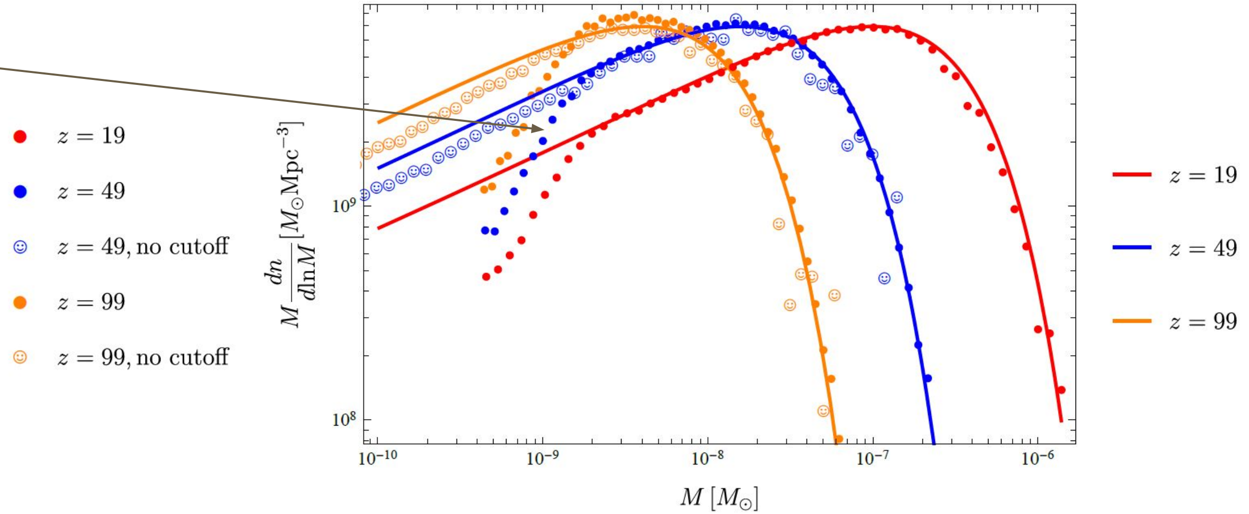
z=24, structure formation

Visualization of the structures in our simulation box. This is a selection box with size 10pc/h. The simulation is gravity only.

H. Xiao, I. Williams, M. McQuinn, 2021

Mass function of Axion Minihalos

Mass function drops due to the cutoff at high k.



Mass function from our simulation data. We are also using a tweaked Sheth-Tormen model to fit it at different redshifts. Data points with smiling faces are from simulation without a cutoff in power spectrum. H. Xiao, I. Williams, M. McQuinn, 2021

Collapse fraction of axion minihalos

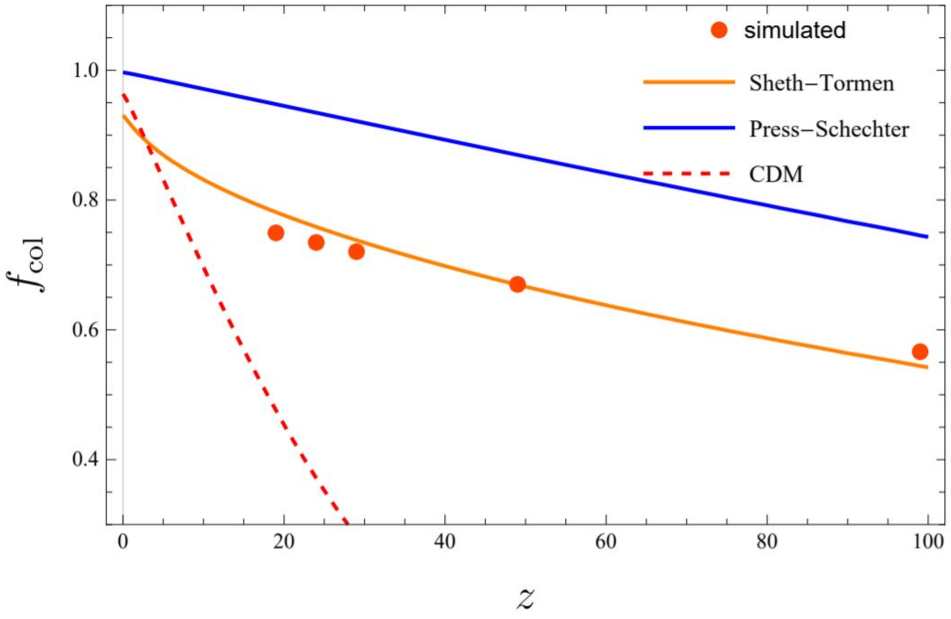
Order one white-noise fluctuations

$\Downarrow$

Most of the axion dark matter has collapsed to minihalos.

A lot of **enhanced substructures at** $M < 10^{-6} M_\odot$

H. Xiao, I. Williams, M. McQuinn, 2021

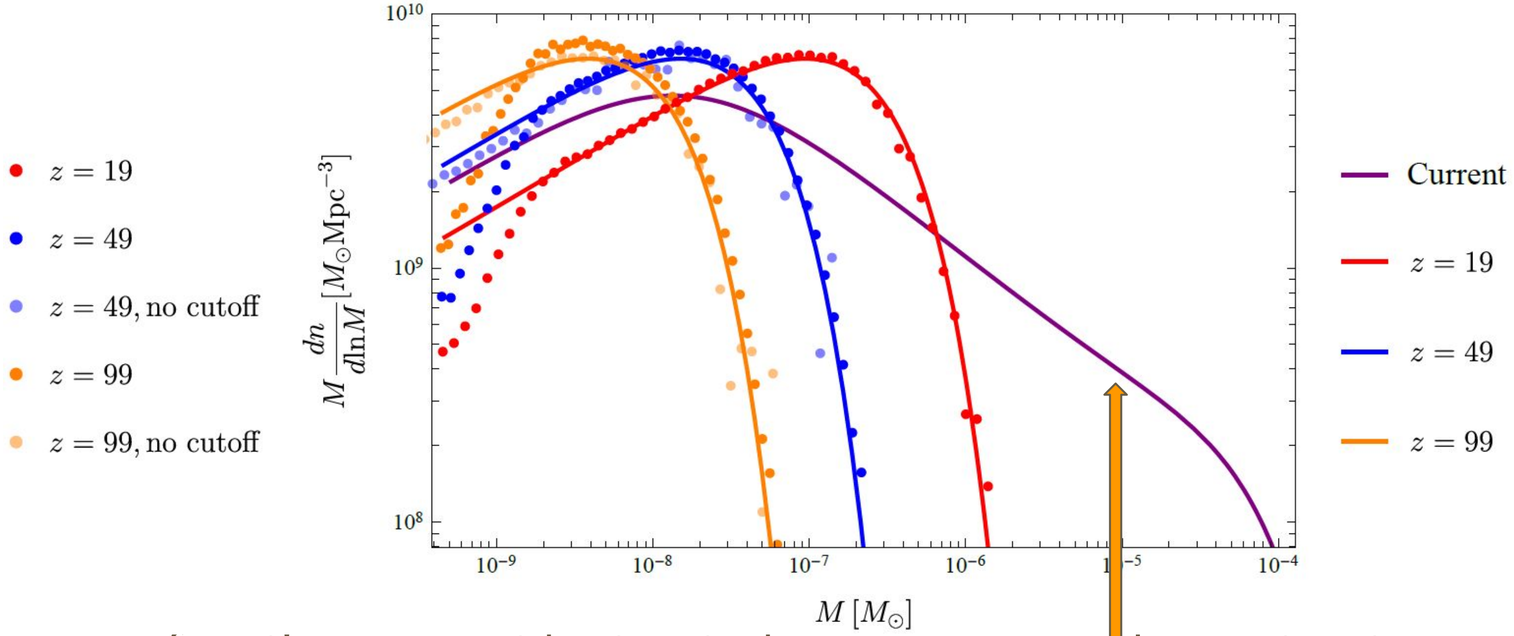


Falling into Large Structures

Assumption: Once minihalos fall into large structures, they stop merging. (Motivated by the high virial velocity of large structures compared to that of minihalos)

Could be inaccurate. Leave for future studies.

Falling into Large Structures



The mass function can not be trusted anymore once large structures formed (when z<20). We compute the current mass function including those incorporated into massive CDM halos.

Density Profiles of Axion Minihalos

Substructures in axion minihalos

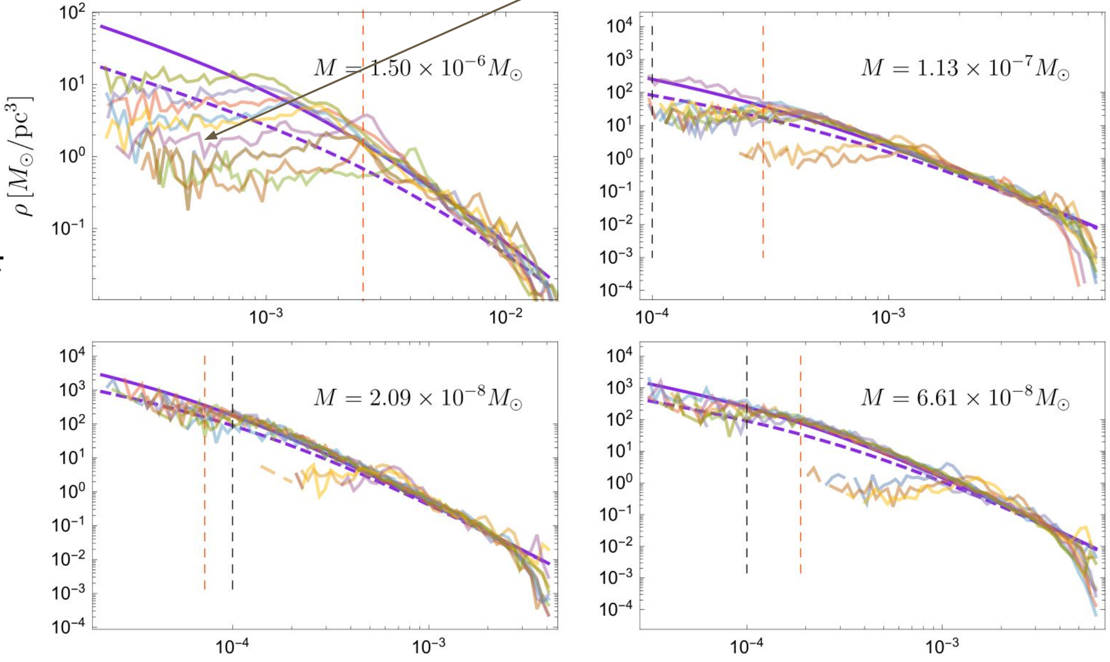
Navarro–Frenk–White (NFW) profile is a good description!

Mass-concentration relation:

$$c(z) \equiv \frac{r_{\rm vir}}{r_s} = \frac{1.4\times10^4}{(1+z)\sqrt{M/(A_{\rm osc}M_0)}}$$

L. Dai and J. Miralda-Escudé, 2019 (Agree with analytical predictions after including a prefactor)

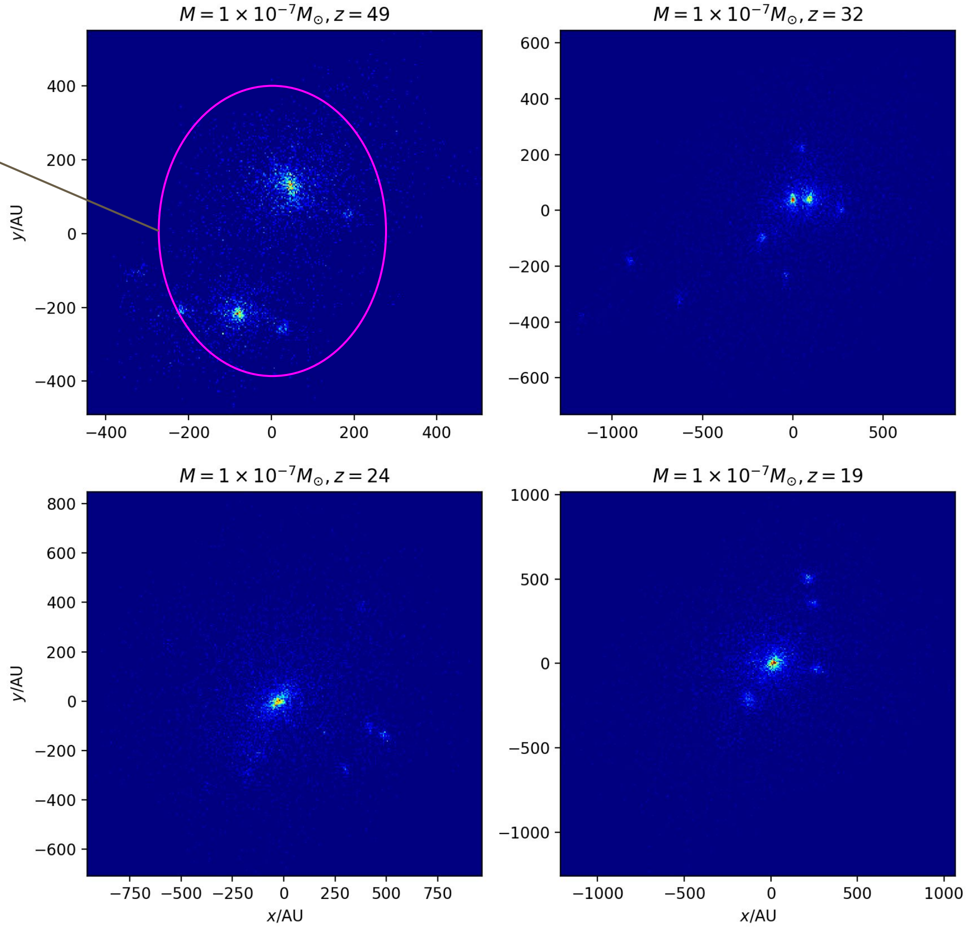
(Solid curve, the concentration of the dashed curve is a factor of two smaller.)



H. Xiao, I. Williams, M. McQuinn, 2021

Bound objects. This is a single axion minihalo.

More likely to have substructures at the **high mass end.**



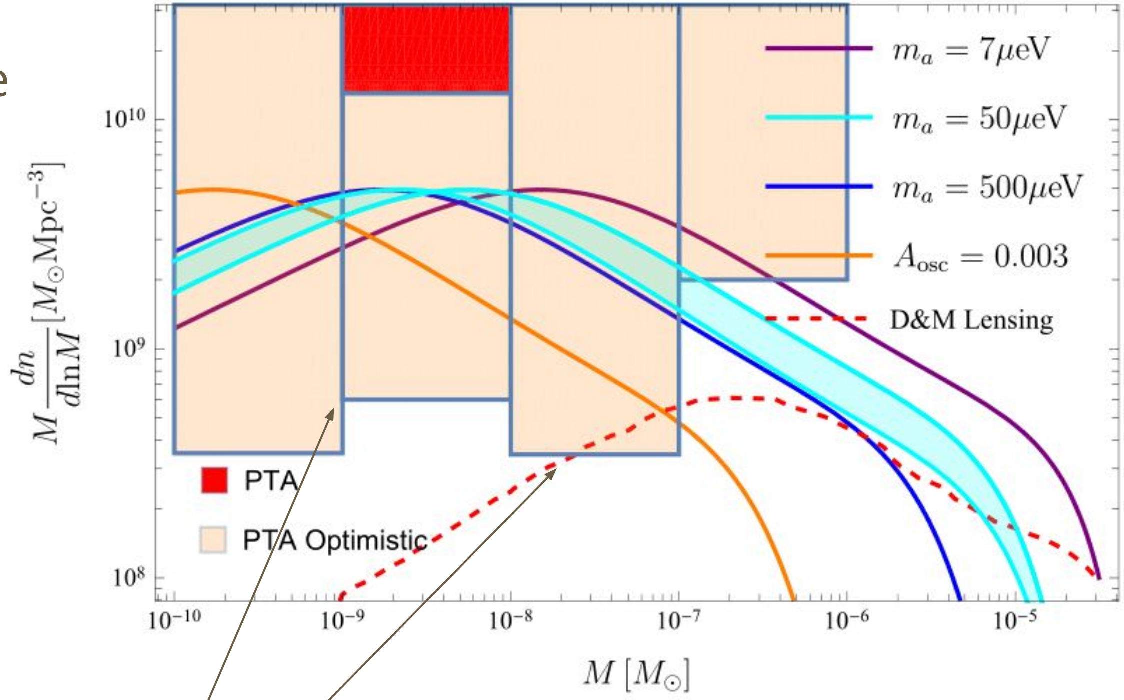
Results for Observations

Microlensing: In our model, the halos are ***not*** concentrated enough.

PTA: Detectable in the future.

Lensing with magnified stars: Detectable in the future.

H. Xiao, I. Williams, M. McQuinn, 2021



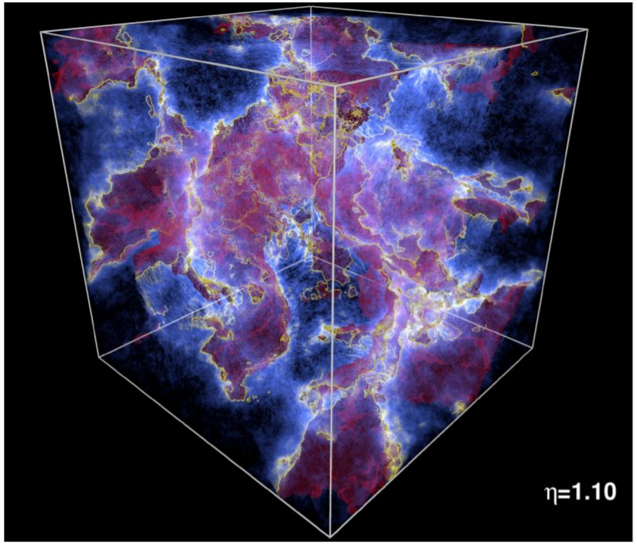
The required abundance of axion minihalos to be detectable

More axions

Topological defects, like axion strings, produce axions.

(Gorghetto, Hardy, Villadoro, 2020. Buschmann, et al., 2021.)

Larger axion mass, less abundance. Axion mass **larger** than the expectation from the vacuum misalignment.



Buschmann, Foster, Safdi, 2019.

Less axions

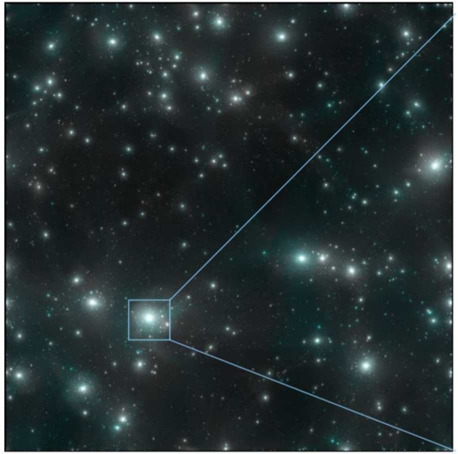
Assumption: A nonstandard thermal history in the early universe like **early matter domination**

Results: extra entropy that dilutes axions.

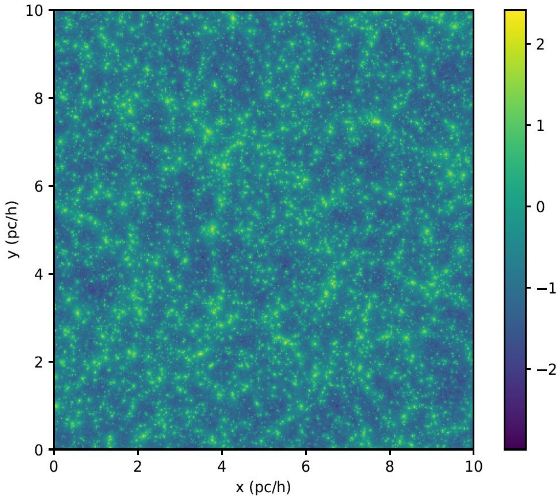
Axion mass smaller than the expectation from the vacuum misalignment. (A.E. Nelson and H. Xiao, 2018)

Also change the mass of axion miniclusters.

Comparison to other axion simulation works



L= 0.864 pc. Whole box collapse at z=99. Cannot contain the largest minihalo. B. Eggemeier, J. Redondo, K. Dolag, J. C. Niemeyer, and A. Vaquero, 2020



L = 50 pc. Whole box linear at z=19. Enough mass to contain the largest minihalo. H. Xiao, I. Williams, M. McQuinn, 2021

Comparison to other axion simulation works

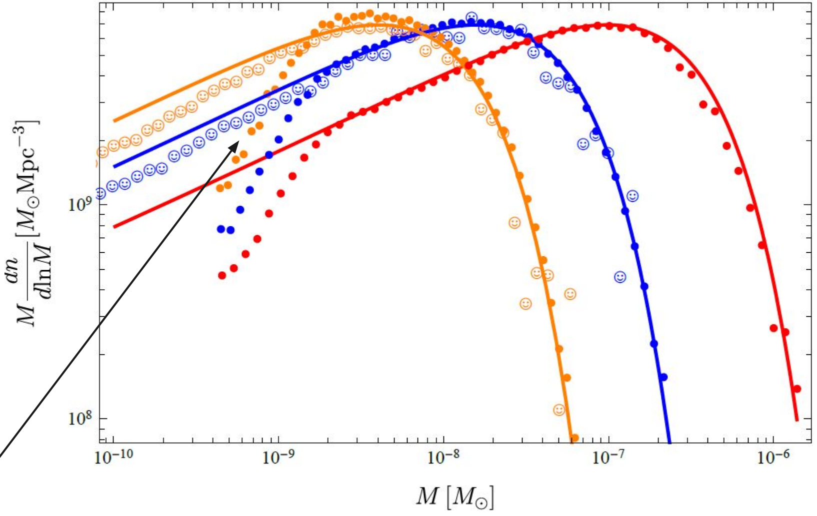
Our initial condition: **white-noise power spectrum**

Other works: Simulating the early Universe evolution (A. Vaquero, J. Redondo, and J. Stadler, 2018.   M. Buschmann, J. W. Foster, and B. R. Safdi, 2020.)

White-noise is the asymptotic behavior at **lower k** ($k < aH$)

Is white-noise good enough?

Yes!



High k power enters here

The axion universe

Our Universe and axion Universe

Our Universe: Standard CDM halos (z~20)------> Cold and dense gas cloud -------> Stars

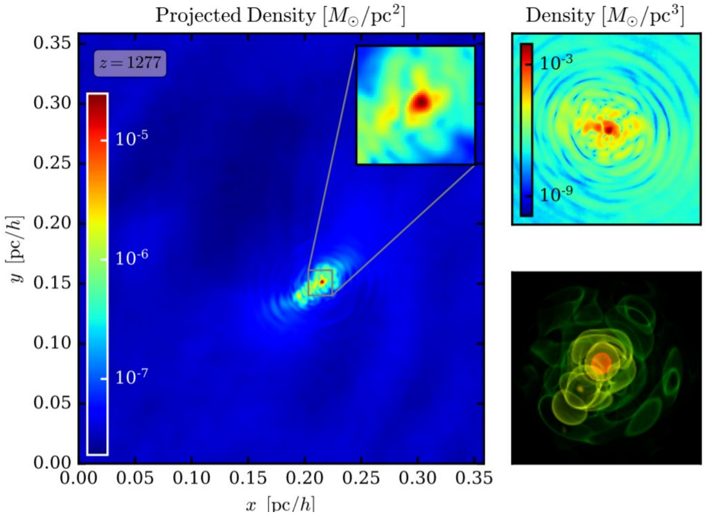
Axion Universe: Axion miniclusters (matter-radiation equality)----> already **cold** (light! Small virial velocity) and **dense** (form early)!-----> Axion stars

Ongoing work with P. Fox and N. Weiner

Axion star formation in axion minihalos

Axions are Bosons. Go through **Bose-Einstein condensation** and form coherent objects in minihalos, known as axion stars.

Our knowledge of axion minihalo populations can help us determine the formation rate of axion stars.



Eggemeier and Niemeyer, 2019

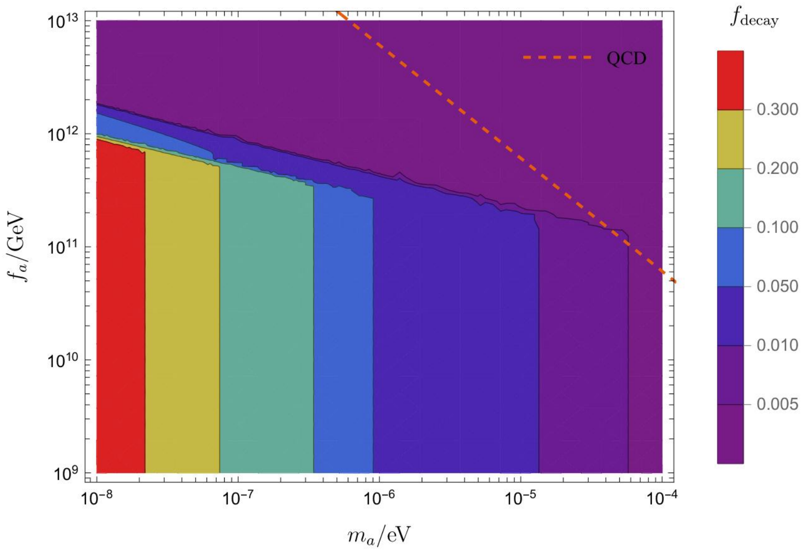
Radiation from axion stars

Critical mass: Axion stars larger than this is unstable, **converting a significant fraction of matter to radiation.** Changes the evolution of the Hubble parameter

Assumption: Axion miniclusters formed from white-noise fluctuations. Minicluster mass given by:

$$M_0 \equiv \frac{4\pi}{3}(\pi L_1)^3 \bar{\rho}_{a,0} = 2.3 \times 10^{-10} \left(\frac{50\mu\text{eV}}{m_a}\right)^{0.51} M_\odot$$

The decay fraction as a function of axion parameters is plotted.



Ongoing work with P. Fox and N. Weiner

Axion-like particles

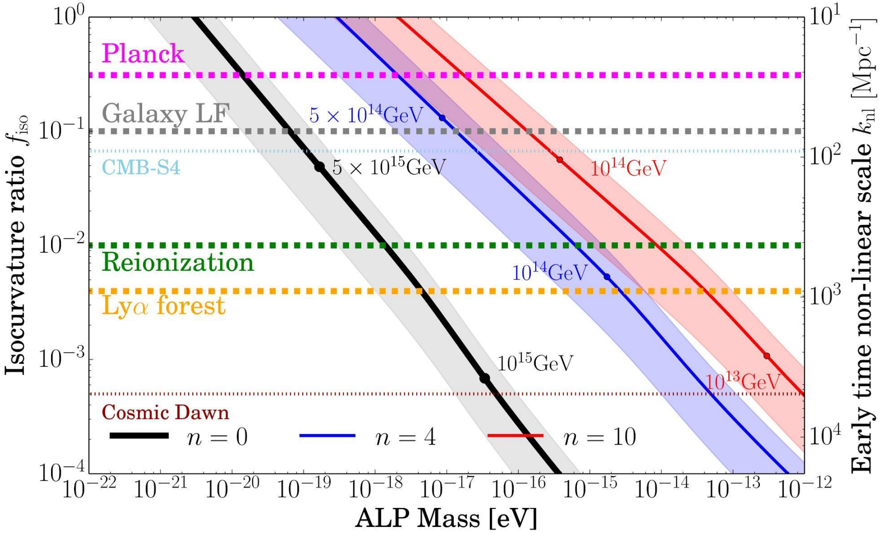
Axion-like particles (ALPs) are **not** necessarily solving the strong CP problem. They can be described by similar particle models and the parameter space is less constricted. (The symmetry breaking scale f_a and the axion mass m_a are independent of each other)

The white-noise simulation is **scale-free**. Therefore our simulation results shall apply to arbitrary scales as far as the white-noise spectrum is concerned..

The constraints for substructures from ALPs

The late-time cosmological matter power spectrum can place constraints on the substructure formation if the axion mass is much lighter than the QCD axion, in which case the structures could be much larger ($\sim 10^5 M_\odot - 10^9 M_\odot$)

The $f_{\rm iso}$ is the ratio of axion isocurvature fluctuations to adiabatic fluctuations at $k = 0.05\mathrm{Mpc}^{-1}$

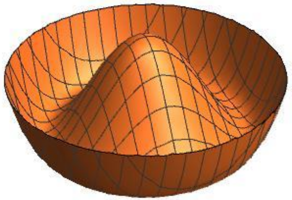


Conclusions

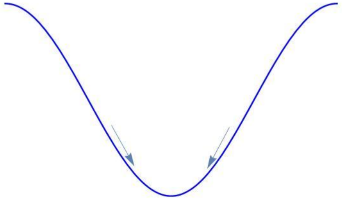
- Enhanced small scale structures! **~75%** of the dark matter in those substructures.
- Predict the current minihalo mass function for the first time with N-body simulations
- Detectable in the future! Even though they are as small as $\sim 10^{-7} M_{\odot}$
- A whole Universe to study! Dark star forming in those structures.

The Invisible Axion

When the Peccei-Quinn theory was proposed, the f_a was believed to be ~100 GeV but soon ruled out by experiments. Now we believe it is somewhere between 10^9-10^12 GeV.



Symmetry breaking: T = 10^12 GeV



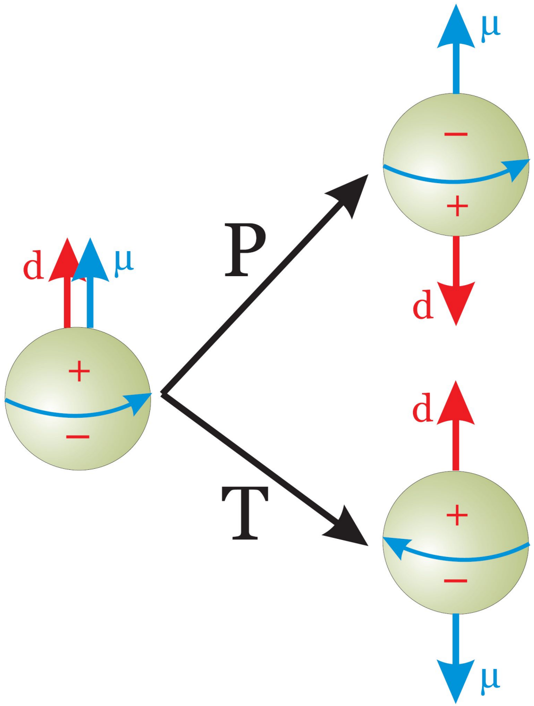
Axion acquires mass: T ~ 200MeV

All the couplings are suppressed by f_a, making axion invisible.

Neutron EDM

The neutron electric dipole moment (eDM) provides a direct measure of the CP violation.

CPT is conserved. Therefore CP must be violated!



A closer look at axions: Peccei-Quinn symmetry

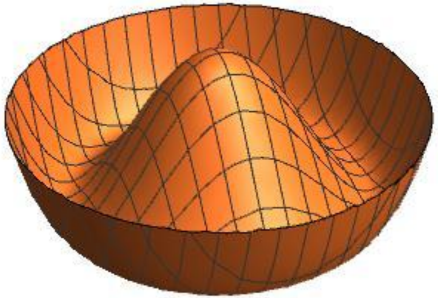
The requirement of axions to solve the strong CP problem: The axion mass should only come from the non-perturbative QCD contribution. Before QCD is turned on, axion should remain massless.

Peccei-Quinn theory: The spontaneous symmetry breaking leads to the massless degrees of freedom, known as the axion since it is the angular field. The potential after the symmetry breaking is:

$$V = (|\phi|^2 - f_a^2)^2$$

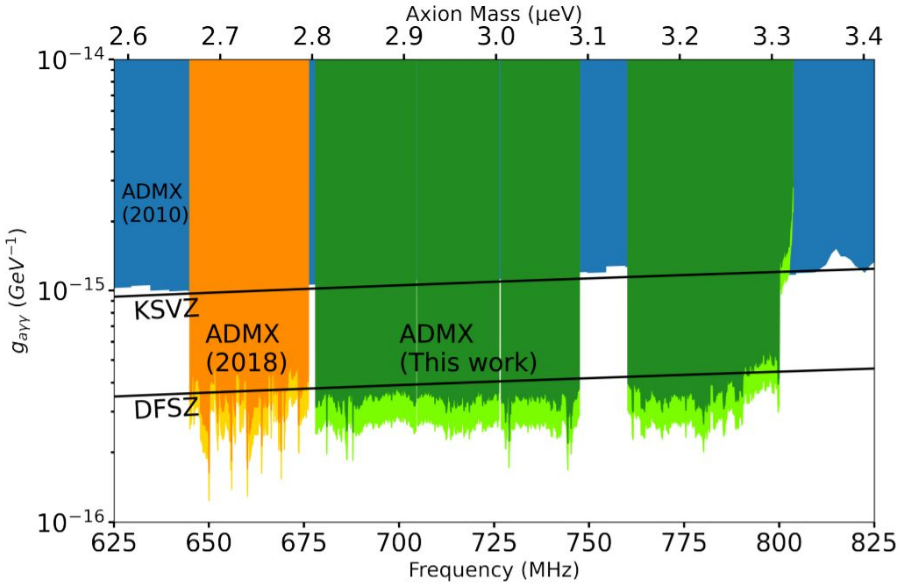
Ignore the radial mode: $\phi = f_a e^{ia(x)/f_a}$ The a(x) field is the axion, a consequence of the spontaneous symmetry breaking.

The symmetry breaking scale also determines the axion couplings to other standard model particles.



ADMX

ADMX exclusion plot.



ADMX collaboration, 2020