The Large Misalignment Mechanism: Resonant structure growth in axion DM

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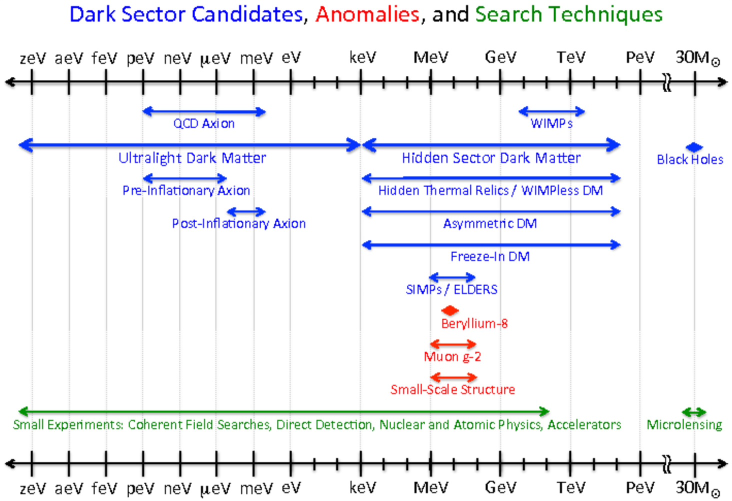
Introduction

Dark Matter



Battaglieri et al. (2017)

Axions

- Originally proposed to solve strong CP problem (QCD axion)
- Potential from explicit nonperturbative breaking of symmetry

  At weak coupling, generically $V(\phi) = m^2 f^2 \left[1 - \cos\left(\frac{\phi}{f}\right)\right]$

  QCD axion: $m^2 f^2 = \Lambda_{QCD}^2$

- More generally, there can be many axion-like particles. Quite generic in string-inspired models: "**String axiverse**"

- Question: Can they be DM? What effects would they have?

Axion cosmology

- For $m \lesssim 1\,\mathrm{eV}$, occupation number is larger than 1

  Treat field like classical wave, not particle
- Natural DM production: **misalignment mechanism**

  Symmetry breaking before inflation

  Very cold, homogeneous field with initial value Φ_0
- Zero mode evolves as $\ddot{\Phi} + 3H\dot{\Phi} + \frac{\mathrm{d}V}{\mathrm{d}\phi}(\Phi) = 0$

Axion cosmology: Free field case

$$V(\phi) = \frac{1}{2}m^2\phi^2 \qquad\qquad \ddot{\Phi} + 3H\dot{\Phi} + m^2\Phi = 0$$

- $H \gg m$: Field frozen, Φ is constant
- $H \lesssim m$: Field oscillates, behaves like **dark matter**, $\rho \propto a^{-3}$

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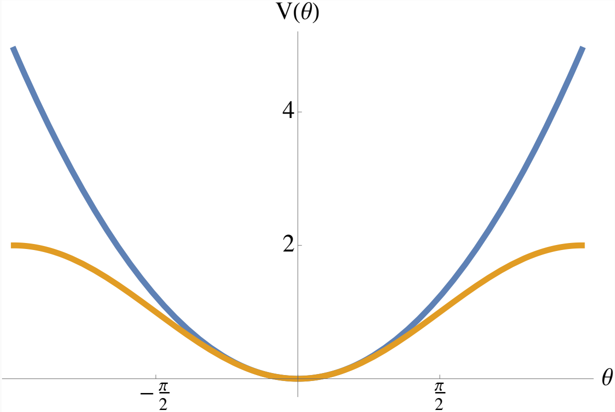
- $H \lesssim m$: Field oscillates, behaves like **dark matter**, $\rho \propto a^{-3}$
- What about spatial structure?
  - $k \ll m$: Behaves like CDM
  - $k \gg m$: Structure washed out by kinetic pressure

Axion cosmology: Self-interactions



H_{osc}: Hubble at the time the field begins oscillating

For "flatter" potentials, H_{osc} will be delayed from naive $H \sim m$

$f_{\pi/2}$: yields proper DM abundance given $\Theta_0 = \frac{\pi}{2}$

Axion cosmology: Self-interactions

- Self-interactions are generic (and generically attractive)
- Most important at earliest times (when $H \sim H_{osc} \lesssim m$)
- Lead to clumping of structure

Structure growth and collapse

Linear regime

For concreteness: $V(\phi) = m^2 f^2 \left[1 - \cos\left(\frac{\phi}{f}\right)\right]$

$$\frac{\phi}{f} = \Theta(t) + \sum_k \theta_k(t) e^{ik\cdot x}$$

- Step 1: Solve for background behavior of zero-mode Θ
- Step 2: Expand in small perturbation θ_k

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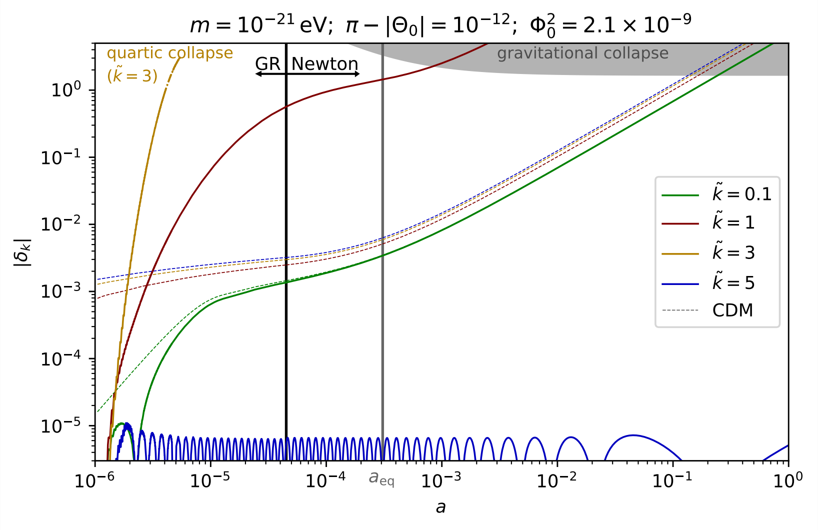
- Step 1: Solve for background behavior of zero-mode Θ
- Step 2: Expand in small perturbation θ_k

$$\theta_k'' + \frac{3}{2t_m}\theta_k' + \left[\cos(\Theta) + \frac{\tilde{k}^2}{t_m}\right]\theta_k \approx 0$$

$$t_m = \frac{m}{2H} \simeq mt \qquad \tilde{k}^2 = \frac{k^2/a^2}{2mH} = \text{const. in R.D.}$$

Linear regime: Representative point



Linear regime: What scales?

Effects strongest for $\tilde{k} \sim 1$, or modes that enter the horizon at the same time the field starts oscillating (when $m \simeq H$)

$$M_s^* \approx 5 \times 10^9 M_\odot \left[\frac{10^{-22}\mathrm{eV}}{m}\right]^{3/2}$$

$$\mathcal{B} \equiv \frac{\rho_s}{\rho_s^{\mathrm{CDM}}} \sim \exp\left(\xi \frac{m}{H_{osc}}\right) \qquad\qquad \xi \sim \mathcal{O}(1)$$

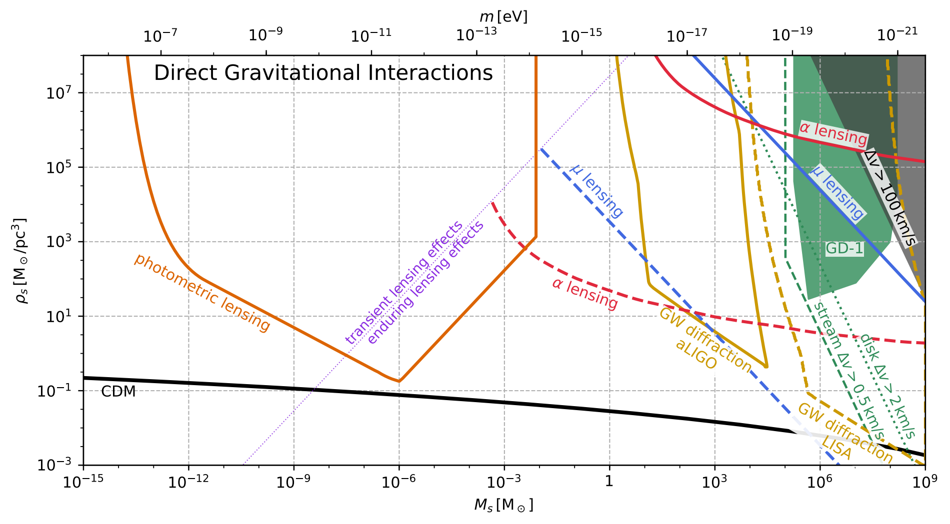
$$r_s^* \sim 100\ \mathrm{pc} \left(\frac{M_s^*}{5\times 10^9 M_\odot}\right)^{1/3} \left(\frac{10^5}{\mathcal{B}}\right)^{1/3} \propto \left(\frac{1}{m}\right)^{1/2}$$

Nonlinear regime

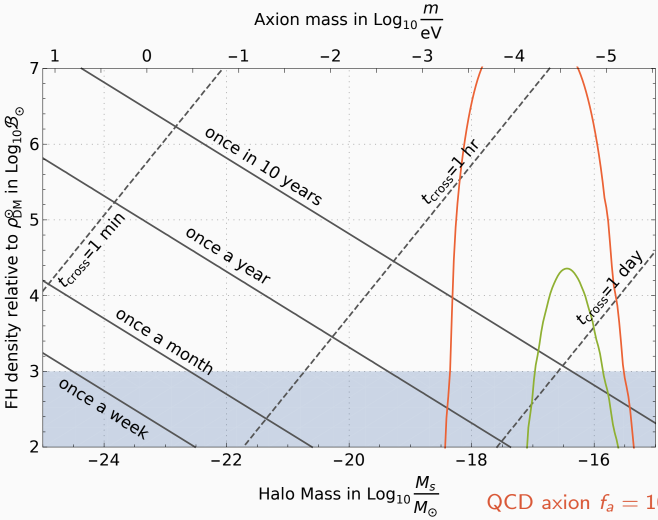
- $\mathcal{B} \lesssim 10^6$: Structures collapse gravitationally before CDM prediction
  - Occurs in matter domination
  - Form compact halo, can cool towards *soliton*
  - For significant boost, $\mathcal{O}(1)$ of DM ends up in halos
- $\mathcal{B} \gtrsim 10^6$: Structures collapse purely due to self-interactions
  - Occurs in radiation domination
  - Form *oscillon*, bound state of unknown lifetime

Signatures

Gravitational interactions



Direct detection



QCD axion $f_a = 10^{10}$ GeV

QCD axion $f_a = 2 \times 10^{10}$ GeV

Direct detection

- Dark matter clumped into halos of characteristic size r_s^*
  - Outside clumps: $\downarrow$ density relative to CDM
  - Inside clumps: $\uparrow$ density, $\downarrow$ velocity dispersion relative to CDM

Direct detection

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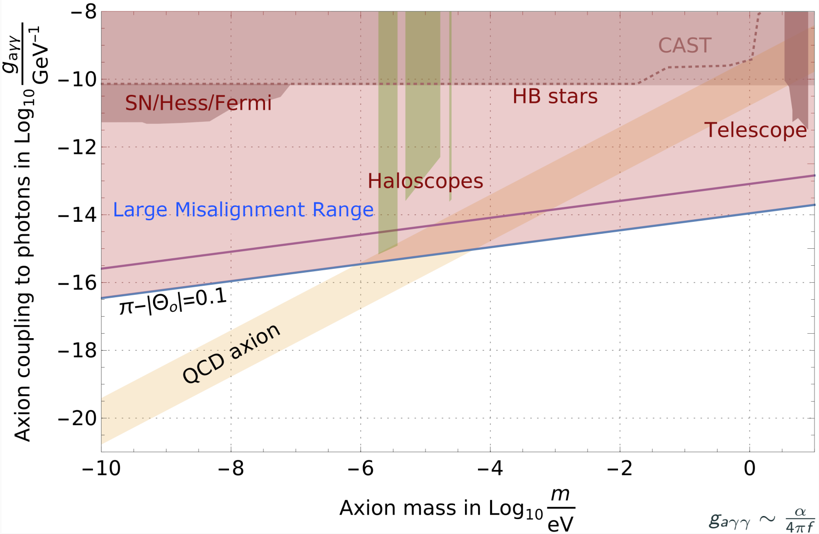
  - Outside clumps: $\downarrow$ density relative to CDM
  - Inside clumps: $\uparrow$ density, $\downarrow$ velocity dispersion relative to CDM
- Changes search strategies
  - Record data off of resonant frequency (i.e. run in broadband mode) for resonant experiments
  - Look for spikes in signal power for duration of crossing time
  - Coherence length is much longer than it would be without clumps $\implies$ reconstruct spatial structure
- Can improve search sensitivity, but must design properly

Direct detection



$g_{a\gamma\gamma} \sim \frac{\alpha}{4\pi f}$

Other signatures

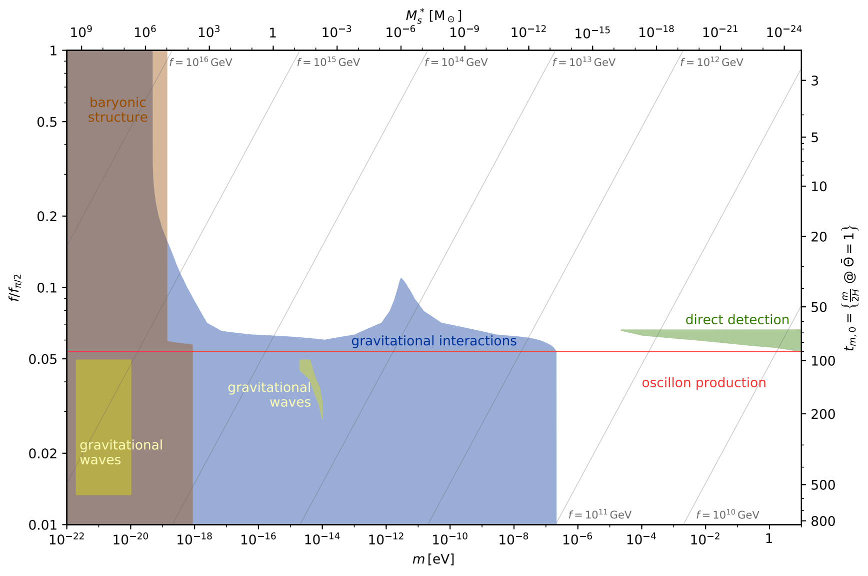
Star formation

- Halos collapse earlier than in CDM $\implies$ denser
- Star formation can occur earlier
- Affected range: Halos from $10^4 M_\odot$ to $10^9 M_\odot$

Gravitational waves

- Collapse due to self-interactions in radiation domination leaves GW background
- Potential to see with pulsar timing arrays, quasar astrometry

Summary of signatures



Summary

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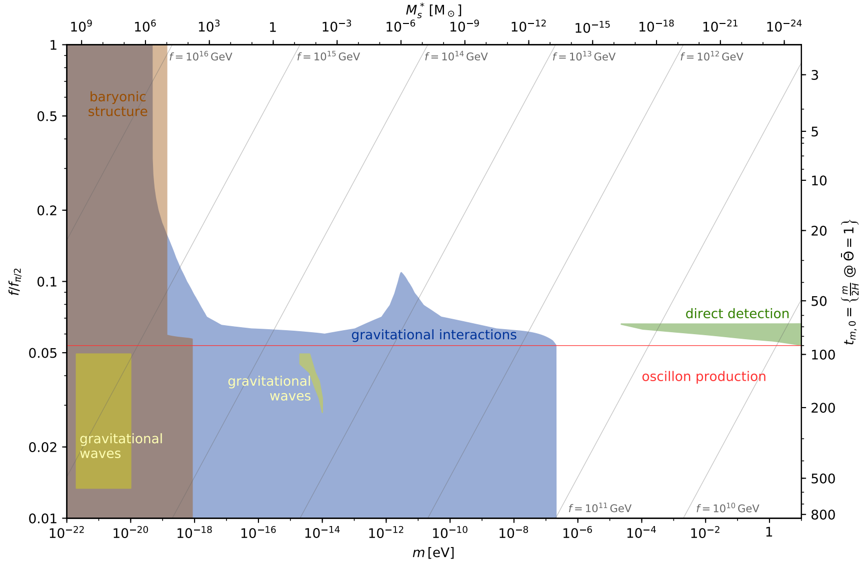
- Axion self-interactions can have significant effects on structure formation in the early universe
- For QCD axion, affected range is $f_a \lesssim 10^{10}\ \mathrm{GeV}$
- Affects direct detection strategies and bounds
- Probes: gravitational interactions, star formation, GW background

- Open questions and future work:
  - Better nonlinear simulations
  - Careful reanalysis of direct detection bounds
  - Better studies of star formation and reionization

Summary



M_s^* [$M_\odot$]
10^9 10^6 10^3 1 10^{-3} 10^{-6} 10^{-9} 10^{-12} 10^{-15} 10^{-18} 10^{-21} 10^{-24}
$f = 10^{16}$ GeV
$f = 10^{15}$ GeV
$f = 10^{14}$ GeV
$f = 10^{13}$ GeV
$f = 10^{12}$ GeV
$f = 10^{11}$ GeV
$f = 10^{10}$ GeV
baryonic structure
gravitational interactions
direct detection
oscillon production
gravitational waves
gravitational waves
$f/f_{\pi/2}$
1 0.5 0.2 0.1 0.05 0.02 0.01
$t_{m,0} = \left\{\frac{m}{2H} @ \bar{\Theta} = 1\right\}$
3 5 10 20 50 100 200 500 800
10^{-22} 10^{-20} 10^{-18} 10^{-16} 10^{-14} 10^{-12} 10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 1
m [eV]