Searching for Axion Radio Broadcasts from the Galaxy:
ADMX Generation 2 and beyond

Aaron S. Chou
Fermi National Accelerator Laboratory
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1. Theory and cosmology constraints
2. Direct detection at micro-eV mass
3. Challenges of higher mass searches
4. Crazy ideas for lower mass search motivated by CMB
AXION™
Nutritional Support for Every Cell of Your Body
Axion model solves the strong CP problem and predicts dark matter

“If the axion does not exist, please tell me how to solve the strong CP problem.”
Frank Wilczek
(Nobel prize for QCD)

“Axions are the thinking person’s dark matter candidate.”
Michael S. Turner

“Axions may be intrinsic to the structure of string theory.”
Ed Witten

Other local axion researchers: Juan Collar, Dan Grin, Craig Hogan, Rocky Kolb, ...

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Q: Why is the neutron electric dipole moment so small?

Naive estimate gives $d_n \approx 10^{-16} \text{ e-cm}$
The neutron electric dipole moment (EDM)

- If exists, must be aligned or anti-aligned with the neutron spin
  - This is the only available spatial axis
- Breaks parity (P) and time-reversal (T) symmetry
  - \( T \) violation = CP-violation
- But the strong interactions of QCD which determine the quark-gluon wavefunctions inside the neutron are explicitly CP-violating!
The CP Problem of Strong Interactions

Characterizes degenerate QCD ground state ($\Theta$ vacuum)

Phase of Quark Mass Matrix

Standard QCD Lagrangian contains a CP violating term

Induces a neutron electric dipole moment (EDM) much in excess of experimental limits

$$L_{CP} = -\frac{\alpha_s}{8\pi} (\Theta - \arg \det M_q) \text{Tr} \tilde{G}_{\mu\nu} G^{\mu\nu}$$

$$0 \leq \Theta \leq 2\pi$$

$$d_n \approx \Theta 10^{-16} \text{ ecm} \approx \frac{\Theta}{10^2} \mu_n < 3 \times 10^{-26} \text{ ecm}$$

$$\Theta \leq 10^{-10} \quad \text{Why so small?}$$
The 1977 Peccei-Quinn solution to the strong-CP problem

- Postulate a new dynamical scalar field which has a two-gluon coupling

- Think like an electrical engineer: Use this field in a cosmological feedback loop to dynamically zero out any pre-existing CP-violating phase angles.

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First make an angular field – the axion \( a \) left over from a new phase transition at high temperature \( f_a \).

The Lagrangian contains a coupling \( L \approx aG/G/f_a \).

VEV \( f_a > 10^9 \text{ GeV} \)
After the quark-gluon phase transition, QCD instanton effects tilt the potential by introducing a term linear in $a$.

$$L \approx a \langle GG \rangle / f_a, \text{ where } \langle GG \rangle \approx \Lambda_{QCD}^4$$

$\Lambda_{QCD}^4$

N.B. Instantons also solve the $\eta-\eta'$ problem in meson spectroscopy.

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The classical axion field rolls down to the true vacuum.

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Energy is minimized when the total phase angle vanishes.

\[ V(A) = -f_a^2 A^2 + \frac{\lambda}{4!} A^4 + \left( \frac{g^2}{32\pi^2} \text{arg}(A) - \frac{\alpha_s}{8\pi} \left( \theta_{QCD} + \theta_{\text{quark}} \right) \right) \langle \langle \tilde{G} \tilde{G} \rangle \rangle \]

The neutron EDM vanishes, solving the strong CP fine-tuning problem.

The axion field zeroes out any other CP-violating phases from the strong or electroweak quark sector.

\[ \Lambda_{QCD}^4 \]

VEV \( f_a > 10^9 \text{ GeV} \)
The initial potential energy density is released as dark matter!!!

Abbott, Sikivie (1983)
Preskill, Wise, Wilczek (1983)
Dine, Fischler (1983)
...

The initial axial \textbf{theta angle} $\theta$, determines the available potential energy to be released. $O(1) \times \Lambda_{\text{QCD}}^4$ of potential energy density is converted into \textbf{ultracold dark matter}.
Dark matter axion mass = harmonic oscillator frequency

\[ m_a = \frac{\Lambda_{QCD}^4}{f_a} < 10^{-3} \text{ eV} \]

VEV \( f_a > 10^9 \text{ GeV} \)

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Searches for the axion rely on the induced coupling of the axion $a$ to photons

\[ \mathcal{L} \equiv -\frac{1}{4} g a F \tilde{F} \approx \frac{\alpha}{8\pi f_{PQ}} a F \tilde{F} \]
\[ = g a \vec{E} \cdot \vec{B} \]

- Coupling is ultraweak – suppressed by the scale $f > 10^9$ GeV
  - Much, much weaker than the weak interactions

- Classical photon fields (Magnets, Lasers) allow semi-classical probes of the coupling $g$ via coherent axion-photon interactions.
  - Need sufficiently electromagnetic energy $B^2 \times (\text{Volume})$ to overcome the tiny value of coupling $g$
  - Need the axion field to also be coherent
The “classic” axion window

Ultraweak couplings to photons are proportional to the axion mass

\[ m_a = \frac{\Lambda_{QCD}^2}{f_a} \]

\[ g \sim \frac{\alpha}{f_a} \sim \frac{m_a}{\Lambda_{QCD}^2} \]
The “classic” axion window

Axion potential energy decays at time $1/H = 1/m_a$. If this is too late in cosmological time, dark matter can be **overproduced** relative to the photons which have redshifted away.
Axions + cosmic inflation = CMB isocurvature

\[ \delta \theta^2 \approx H_i^2 / f_a^2 \]  (Seckel & Turner, 1985)

Inflation creates a spectrum of radiation in the form of gravitational waves and axionic waves (isocurvature perturbations in CMB). **Neither has yet been detected.**
Clumps of correlated theta after the PQ phase transition

Just like spin domains in a ferromagnet immersed in a background B field. **Larger values correspond to larger initial potential energy density** to be released as dark matter when $H \approx m_a$

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Turner & Kolb
The Early Universe
**Classic window:** PQ happens after inflation, creating many bubbles in our horizon

\[ \theta_{\text{rms}} \approx 1 \text{ which fixes the initial potential energy to be } \approx \Lambda_{\text{QCD}}^4 \]

\[ m_a \text{ must be large-ish to allow early release of potential energy to avoid overproducing CDM} \]

Many domains in each cosmological horizon. \[ \sqrt{\left\langle \delta \theta^2 \right\rangle} \approx 1 \]
In the classic window, isocurvature fluctuations are on scales too small to be resolved by the CMB

20% of axion dark matter is in miniclusters formed by the initial correlation length $1/H_{\text{QCD}}$

$M_{mc} \sim 10^{-12} M_{\odot}$

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C. Hogan, Rees, 1988
Kolb, Tkachev, 1993
Kolb, Tkachev, 1996
Anthropic window: PQ happens before inflation and is not restored by reheating $\Rightarrow$ $\theta$ is single-valued

Humans happen to live in a bubble where $\theta \ll 1$

Initial potential energy is small, so late release of energy is okay $\Rightarrow$ $m_a$ can be tiny.

But, inflaton scale must be small to avoid CMB isocurvature constraints. $\delta \theta^2 \approx H_i^2/f_a^2$

Can be ruled out if BICEP2 is correct.

Hertzberg, Tegmark, Wilczek (2010)
Taken to the extreme – the potential energy for ultralow mass axions has not yet decayed and could be the dark energy.

Hlozek, D. Grin, Marsh, Ferreira, 2014
How to detect axion dark matter in the classic window: $10^{-6}$ eV < $m_a$ < $10^{-4}$ eV?

Note: Fit to Lambda-CDM data predicts $m_a = 71 \pm 2$ micro-eV (!) Visinelli, Gondolo (2014)
Observation 1: The local dark matter axion number density is humongous!

- Local dark matter distribution has density around 300 MeV/cc

- For 300 GeV mass, local WIMP densities are around 1/liter

- For $10^{-6}$ eV axion mass, the local axion density is $10^{14}$ / cc

Imagine putting $10^{17}$ jellybeans in this jar.

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Observation 2: the dark matter axion field is coherent on sufficiently small spatial and temporal intervals.

Dark matter has approximately a Maxwell-Boltzmann velocity distribution with $\langle v \rangle \approx \sigma_v \approx 200 \text{ km/s} \approx 10^{-3} c$

Axion energy spread:
\[ \sigma_E = m_a \langle v \rangle \sigma_v \approx 10^{-6} m_a \]

and momentum spread:
\[ \sigma_p = m_a \sigma_v \approx 10^{-3} m_a \]

For $m_a \approx 10^{-6} \text{ eV} \approx 1 \text{ GHz}$, this gives coherence over:
\[ t_{\text{coh}} = \text{milliseconds} \]
\[ L_{\text{coh}} = 100 \text{ meters} \]
The local axion dark matter can be regarded as a classical wave with properties similar to those of a modern solid-state laser.

Huge number density, Linewidth $\approx$ kHz

\[ |\vec{A}| \approx \frac{\sqrt{P_{\text{laser}} Z_0}}{\omega} e^{i(k \cdot \vec{x} - \omega t + \phi)} \]

\[ a \approx \frac{\sqrt{2 \rho_a}}{m_a} e^{i(k \cdot \vec{x} - \omega t + \phi)} \]

Except, we don’t know the color of this mystery laser pointer, and it doesn’t interact much with our detectors.....

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Axion Dark Matter Search (ADMX)

- On lab scales < 100m:
  \[ a = \frac{\sqrt{2} \rho_a}{m_a} e^{im_a t} \]

- In a constant background B field, the axion field sources a classical EM field via the modified Maxwell’s Equations:
  \[
  \epsilon \nabla \cdot \vec{E} = g_{\alpha \gamma \gamma} B_0 \cdot \nabla a
  \\
  \nabla \times \vec{B} - \epsilon \partial_t \vec{E} = -g_{\alpha \gamma \gamma} B_0 \partial_t a
  \\
  \partial_t^2 a - \nabla^2 a + m_a^2 a = -g_{\alpha \gamma \gamma} \vec{E} \cdot \vec{B}_0.
  \]

- Dark matter axions act as an oscillating source current which produces real RF photons

- \( \rightarrow \) RF photon frequency = axion mass

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Use a high-Q cavity as a **resonant antenna** to enhance the conversion of dark matter power into RF power

**But, the cavity must be appropriately sized.**

- Initial state axion $E = m_a, \ p \approx 0$
- Final state photon $E = p = m_a$
- The cavity must absorb the excess recoil momentum $m_a$
- Just like a resonant dipole antenna, this is optimized when the size of the cavity is matched to the momentum transfer
- Current experiment uses a 50cm cavity to search at $m_a = \text{few micro-eV} \approx 1 \text{ GHz}$

Need $d_{\text{cavity}} \approx 1/m_a$
Even with cavity enhancement of the scattering cross-section, the signal strength is ultraweak

\[ P_a = g^2 \frac{\rho_a}{m_a} B_0^2 V \times \min(Q_{\text{cav}}, Q_a) \]

\[ \approx 10^{-21} \text{ W} \quad @ \ m_a = 10^{-6} \text{ eV} \]

Best case scenario with B=8 T, V=0.2 m^3 MRI magnet, and copper cavity Q = 10^5
ADMX Generation 2 Project located at U.Washington

Cryogenic operation is necessary to reduce thermal noise

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Cavity = high-Q resonant antenna

Need to tune antenna to scan for the axion transmission frequency.

If $P_{\text{signal}} < P_{\text{noise}}$, need to average over many measurements to detect the small signal power excess. Integration time required at each tuning is given by the Dicke radiometer equation:

$$t_{\text{tune}} = \left( \frac{P_{\text{noise}}}{P_{\text{signal}}} \right)^2 \times \frac{1}{\Delta f}$$

Must keep this below few minutes to finish the radio scan over $Q=10^5$ bins in a graduate student lifetime!
Read out signal power with quantum-limited amplifier feeding a superheterodyne radio receiver

SQUID for 500 MHz < f < 1 GHz,
Josephson Parametric Amplifier for 1-20 GHz

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Historical context and significance:

Clarke and Kinion (2011) provided a detailed analysis of the noise temperature in quantum-limited detectors, highlighting the importance of quantum noise in low-frequency applications.

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50 cm
Also keep physical temperature low to avoid thermal photons in the cavity

At $m_a = 4$ micro-eV, $f = 1$ GHz, $Q=10^5$, $df = 10$ kHz, the signal power is tiny:

$$P_{\text{signal}} < 10^{-21} \text{ W}$$

At physical temperature $T = 1$ K, the signal power is swamped by thermal noise:

$$P_{\text{noise}} = kT \, df = kT \times f/Q \approx 10^{-19} \text{ W}$$

At $T = hf = 40$ mK, the noise is quantum-limited and is comparable to the signal:

$$P_{\text{noise}} = hf \, df = hf \times f/Q \approx 10^{-21} \text{ W}$$

$\rightarrow$ 1 signal photon + 1 noise photon per 10 kHz resolution sample, gotten in $10^{-4}$ seconds
The shape of the axion radio spectrum can be resolved

ADMX has purchased and is now commissioning a new dilution refrigerator to reach quantum-limited noise.

The favorable S/N ratio allows additional integration time for finer frequency resolution when the axion broadcast is discovered.

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Debris flows leave kinematic substructure while being spatially homogeneous

Normalized DM velocity distributions from Via Lactea 2 simulation,

Once axions are detected, the shape of the local axion DM power spectrum can be easily measured to determine deviations from pure Maxwell-Boltzmann

For 2x frequency resolution, need 2x sample time. Half-power in each bin requires 4x samples. Total 8x integration time is easy!
How likely are we to see narrow-line substructure in the axion power spectrum?

Fraction of particles in cold streams with density \( \rho_s \) at 10 kpc

A 20% chance to see a stream containing 1% of the DM

Around 10 local streams containing 0.1% of the DM

Unlikely to see single streams containing all of the DM

Resolving narrow, weak lines is tough....

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Take time-series data just like in radio astronomy. Cross correlation signal disappears when:
L > 1/Δp ~ 100m for virialized dark matter and >1 km for cold flows.

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Axion Dark Matter Experiment (U.S. DOE Gen2 project)
Goal is to cover preferred axion mass region from 500 MHz – 10 GHz
How to cover higher mass regions?

Cavity Frequency (GHz)

Axion Coupling $|g_{a\gamma}|$ (GeV$^{-1}$)

Axion Mass (µeV)

Non RF-cavity Techniques

White Dwarf and Supernova Bounds

Too Much Dark Matter

ADMX LF
ADMX Published Limits
ADMX M1
ADMX M2
ADMX HF

Axion Cold Dark Matter

“Hadronic” Coupling

Warm Dark Matter

Minimum Coupling

ADMX Gen2 2015-2019

Gen3 experiment?
Going to 10x mass drastically reduces the signal-to-noise ratio...

Simply scaling down the cylindrical cavity dimensions to match the shorter axion wavelengths does not work.

The volume and hence signal power is decreased by \((\text{radius ratio})^2 = 100\).

The quantum noise power times noise bandwidth is increased by x100.

\(\rightarrow\) the time required to scan and detect the signal increases by a large factor:

\[
t_{\text{octave}}^{\text{cylinder}} = 15 \text{ years} \times \left(\frac{8 \text{ T}}{B}\right)^4 \left(\frac{1 \text{ m}}{l_m}\right)^2 \left(\frac{m_a}{10^{-5} \text{ eV}}\right)^{19/3}
\]

(Copper cavity)

Aaron S. Chou, 9/10/14
Idea #1 to reach $m_a = 40 \text{ micro-eV} = 10 \text{ GHz}$

Recover the lost volume by using a different form factor for the cavity. The axion is a scalar – we only need one cavity dimension to be matched to the axion wavelength.

A rectilinear cavity has a much larger volume than a cylindrical cavity of the same frequency.

A scan at 10 GHz now takes only days instead of years:

$$t_{\text{octave}}^{\text{rectilinear}} = 8 \text{ days} \times \left( \frac{8 \text{ T}}{B} \right)^4 \left( \frac{1 \text{ m}}{l_m} \right)^4 \left( \frac{m_a}{10^{-5} \text{ eV}} \right)^{13/3}$$

$$1/m_a = 3 \text{ cm}$$

Aaron S. Chou, 9/10/14
Using nested cylinders is even better!

Another factor of pi in volume
→ Factor of 10 reduction in integration time

1/mₐ = 3 cm

Aaron S. Chou, 9/10/14
Idea #2: Follow the CMB community and replace quantum-limited radiometers $T_n \geq \hbar \omega / k$ with shot-noise-limited bolometers.

How to re-engineer to achieve quantum-limited performance with 0 thermal photon background?

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How to search for lower mass axions $m_a < 10^{-6}$ eV, $f < 100$ MHz in the anthropic window?

- Excluded if CMB B-mode detection is real, since isocurvature not seen.
- But, preferred by string theory model builders

- $1/m_a > 3$ meters – larger than reasonable magnet bore sizes
  - Coherent enhancement of power transfer using resonant antenna cavity is not possible $\Rightarrow$ signal power at each tuning is expected to be low.

- Observation: capacitors and inductors still work in RF-shielded Faraday cages.
  - Faraday cages are like cavities which suppress far-field radiation from these components
  - Near-field electromagnetic configurations are unaffected
  - Possible to directly detect the near-fields sourced by the axions?
Skip the resonant cavity and instead coherently build up signal power using high-Q superconducting LC resonator

Sikivie, Sullivan, Tanner, arXiv:1310.8545

LC resonators of the same resonant frequency can be made much smaller than the equivalent cavity resonator by using low-loss dielectrics to reduce the speed of light in the capacitors.
What if we could afford a room full of radios?
To speed up the scan, use comb of resonant filters to simultaneously tune to 1000 frequencies

\[
\begin{align*}
\text{SQUID ammeter output can be digitized in the time domain. A real-time FFT then provides simultaneous and continuous readout of power build-up in all resonators.} \\
\rightarrow \text{Save factor of 1000 in scan time.}
\end{align*}
\]

\[
L \text{CA}_{\text{Array}} = 14 \text{ days} \times \left(\frac{10^3}{N_{\text{tuners}}}\right) \left(\frac{10^4}{Q_{LC}}\right)^2 \left(\frac{L}{1 \mu H}\right)^2 \left(\frac{T}{1 K}\right)^2 \left(\frac{10 T}{B}\right)^4 \left(\frac{1 m}{l_m}\right)^4 \left(\frac{1 m}{r_m}\right)^8 \left(\frac{10^{-7} \text{ eV}}{m_a}\right)^5
\]

Aaron S. Chou, 9/10/14
First-ever deployment of frequency multiplexed readout was in the South Pole Telescope

2001: ACBAR
16 detectors

2007: SPT
960 detectors

2012: SPTpol
~1600 detectors

2016: SPT-3G
~15,200 detectors

2020?: CMB-S4
100,000+ detectors

Detector sensitivity has been limited by photon “shot” noise for last ~15 years; further improvements are made only by making more detectors!

Slide from B. Benson (FNAL)
Superconducting multiplexed readouts are currently being implemented in multi-pixel astro detectors (SPICA, SPT, MKIDs at FNAL)

Fig. 1 Chip (36 × 28 mm²), containing 160 LC resonators, 100:1 inductive and 10:1 capacitive AC-bias voltage division, on-chip summing (top), and individual bonding pads (left and bottom) to detector pixels. (Color figure online)

M.P.Bruijn et.al, 2013

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Axion $\rightarrow$ current amplitude transfer function vs frequency

$\Delta f_{\text{comb}} = m_a/10^3$ for $10^3$ radio tuners

$Q=10^4$ resonant enhancement to beat amplifier noise

Resonance bandwidth $\delta f_{\text{res}} = m_a/10^4$

$= \Delta f_{\text{comb}} / 10$

Narrowband axion signal hiding within one of the resonances!!!
Conclusions

• After 20 years of detector R&D, the axion community has finally reached sensitivity to dark matter axions in the 1-10 micro-eV mass range
  – DOE has funded ADMX as a generation 2 dark matter project, and it will run from 2015-2019

• Axion astronomy will tell us about the history of the Milky Way

• Higher mass axions within the cosmology-allowed window still pose an extreme challenge due to the poor scaling of the signal-to-noise ratio
  – U.Chicago/Fermilab/Argonne(?) to engage in detector R&D to meet this challenge

• Lower mass axions are still viable and preferred by many theorists

• Successful techniques developed in the CMB/FIR community may be usefully appropriated for dark matter axion searches.

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Backup slides
Scaling of signal power with increased mass or frequency is **poor**

\[ P_a = g^2 \frac{\rho_a}{m_a} B_0^2 V \times \min(Q_{\text{cav}}, Q_a) \]

Using \( g \approx \alpha \frac{m_a}{\Lambda_{QCD}}^2 \), rewrite as

\[ P_a = \frac{\alpha^2}{\pi^2} \frac{\rho_a}{\Lambda^4} B_0^2 V Q m_a \]

Cylindrical cavity \( V \) scales as \( m_a^{-2} \), and \( Q \) scales as \( m_a^{-2/3} \) due to copper skin depth.

\( \Rightarrow P_{\text{signal}} \sim m_a^{-5/3} \)

Linewidth and hence noise bandwidth scales as \( m_a/Q \) or \( m_a^{5/3} \)

\( \Rightarrow P_{\text{noise}} \sim m_a^{+8/3} \)

**Signal-to-noise ratio scales as** \( m_a^{-13/3} \) – even for quantum-limited noise