Searching for the Decay of Axion Dark Matter

Samuel J. Witte

Based on 1805.08780
In collaboration with Andrea Caputo and Carlos Peña-Garay

(Ongoing work with A. Caputo, C. Peña-Garay, M. Taoso, M. Regis, J. Miralda, J. Salvado)

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elusives neutrinos, dark matter & dark energy physics

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Showing that the Decay of QCD Axion Dark Matter is not Hopelessly Invisible

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Outline

The Strong CP Problem

Strong CP Problem: QCD Langrangian has non-perturbative term

$$\mathcal{L}_{QCD} \propto \mathcal{L}_{Pert} + \bar{\Theta}\frac{g^2}{32\pi^2}G^{a\nu\mu}\tilde{G}_{a\nu\mu}\,, \tag{1}$$

Meanwhile, the ED moment of the neutron d_n

$$d_n \sim 5 \times 10^{-16}\,\bar{\Theta}\,\mathrm{e\,cm} \qquad \lesssim 6 \times 10^{-26}\,\mathrm{e\,cm} \tag{2}$$

Experimental limit

Perhaps the most popular solution: Introduce new global $U(1)_{PQ}$ symmetry that is spontaneously broken

→ SSB gives rise to new pNGB, the 'axion'

Properties of the Axion

Once model defined, QCD axion pheno reduced to one parameter with

$$m_a \sim 5.7 \times \left(\frac{10^{12}\,\mathrm{GeV}}{f_{PQ}} \right) \mu\mathrm{eV} \tag{3}$$

Lagrangian for axion-SM interactions given by

$$\mathcal{L} \supset \quad C_g \frac{a}{f_{PQ}} G\tilde{G} + \frac{\partial_\mu a}{f_{PQ}} \sum C_{a\psi} \left(\bar{\psi} \gamma^\mu \gamma^5 \psi \right) + C_{a\gamma} \frac{a}{f_{PQ}} F\tilde{F} + \cdots \tag{4}$$

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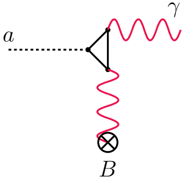

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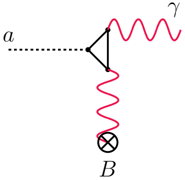

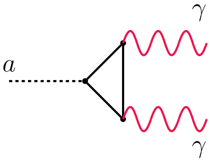

The *'Invisible Axion'*

Original PQWW solution set $f_{PQ} \sim$ EW scale
$\rightarrow f_{PQ} \sim 250$ GeV implies $m_a \sim 200$ keV

- Ruled out by astrophysical and laboratory experiments (rare Kaon and quarkonium decays)

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While large, perhaps not completely hopeless...

Production in the Early Universe

If we require $\Omega_{DM} \sim \Omega_a$, what can we say about m_a?

- PQ symmetry is *broken* before inflation
  - Ω_a dependent upon initial condition $\Theta_i \in (0.3, 3)$ favoring $m_a \in (10^{-6} - 10^{-4})$ eV Irastorza and Redondo (2018)
- PQ symmetry is *broken* after inflation
  - Axion field takes random values in smaller domains
  - Averaging initial values, one finds

$$\Omega_a^{(VR)} h^2 = (3.8 \pm 0.6) \times 10^{-3} \left(\frac{f_a}{10^{10}\,\mathrm{GeV}} \right)^{1.165} \quad (7)$$

Borsanyi et al (2016); Ballesteros, J. Redondo, A. Ringwald and C. Tamarit (2017)

  - $\rightarrow m_a \gtrsim 28\mu$eV

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Production in the Early Universe

(Post inflationary scenario continued)

Difficultly arises in contribution from topological defects (strings and domain walls)

- Contribution from strings estimated to be

$$\Omega_a^{(s)} h^2 \simeq 7.8^{+6.3}_{-4.5} \times 10^{-3} \times N_{DW}^2 \left(\frac{f_a}{10^{10}\,\mathrm{GeV}} \right)^{1.165} \qquad (8)$$

  (N_{DW} model-dependent integer)

  Ballesteros, J. Redondo, A. Ringwald and C. Tamarit (2017)

- For $N_{DW} = 1$, string-wall systems collapse and lead to prediction $m_a \sim (58 - 150)\mu$eV

  M. Kawasaki, K. Saikawa and T. Sekiguchi (2015)

- Recent field theory simulation that unifies treatment of VR, strings, and collapse predicted $m_a = (26.2 \pm 3.4)\mu$eV

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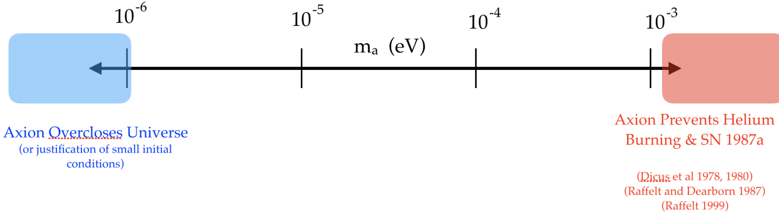
The Mass of QCD Axion Dark Matter



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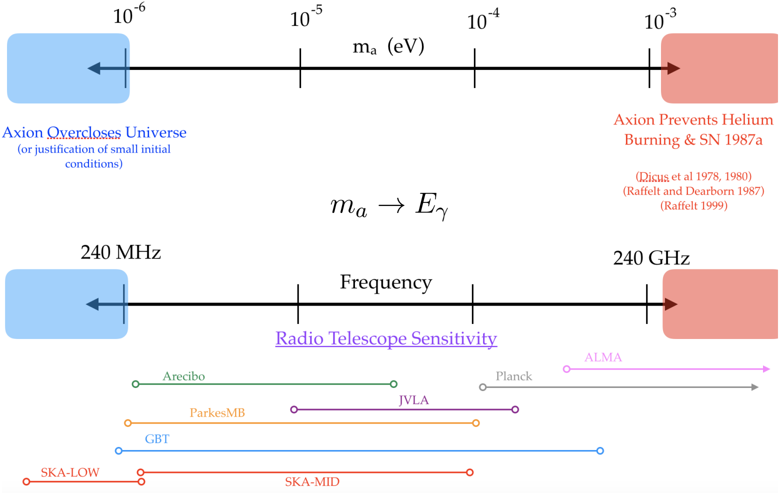
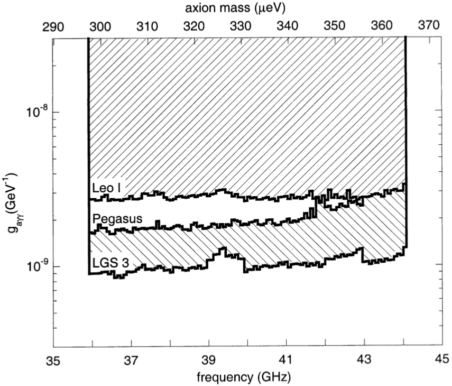


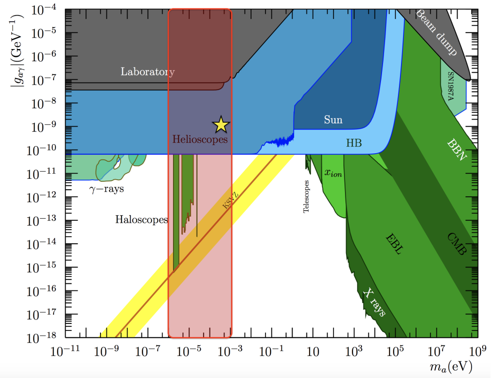
First Radio Search for Axion Decay

Idea first proposed and implemented by B. D. Blout et al (2001), but not discussed further



Last ~ 17 years has lead to enormous improvements in the field...

Status of Axion Searches



Irastorza and Redondo (2018)

Current and future searches by *e.g.* ADMX, MADMAX, IAXO, ALPS, RADES, HAYSTAC, CULTASK, ... will attempt to cover this region

Recent Studies on Indirect Detection of Axions

- Axion conversion in Galactic Center Kelley and Quinn (2017)
  - Sigl (2017) showed inhomogeneity of $\vec{B}$ reduces sensitivity to $g_{a\gamma\gamma}$ by ~ 6 orders of magnitude
- Stellar winds from Wolf-Rayet stars Sigl (2017)
  - Large uncertainties
- Axion conversion near neutron stars Huang, Kadota, Sekiguchi, and Tashiro (2018); Hook, Kahn, Safdi, and Sun (2018)
  - See Ben Safdi's talk

Primakoff Effect on Galactic Scales

- Flux density given by

$$S_{a\to\gamma} \propto \int d\Omega\, d\ell\, \rho_a(\Omega,\ell)\, \rho_m(k,\Omega,\ell)\,, \tag{9}$$

with ρ_m capturing the magnetic energy density about wavenumber k

- For turbulent magnetic fields (with rms value B, and coherence length l_c)

$$\rho_m(k) \sim \frac{B^2}{8\pi} f(k) \qquad f(k) \simeq (k\, l_c)^{-2/3} \tag{10}$$

Sigl (2017)

- $k = \frac{1}{20}\frac{\mu eV}{m_a}\,\mathrm{cm}^{-1}$ and $l_c \sim$ pc, then suppression by $f \sim 10^{-13}$

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Axion Decay $a \to \gamma\gamma$

- Flux density from spontaneous decay

$$S_{sd} \propto \int d\Omega \, d\ell \, \frac{\rho_a(\Omega, \ell)}{\tau_a} \tag{11}$$

- Stimulated emission (photons produced in background of photons with same energy), collision term of Boltzmann equation leads to

$$\propto |\mathcal{M}_{a\to\gamma\gamma}|^2 \left[n_a(n_\gamma + 1)^2 - n_\gamma^2(n_a + 1) \right] \tag{12}$$

- In limit $n_\gamma \ll n_a$ gives

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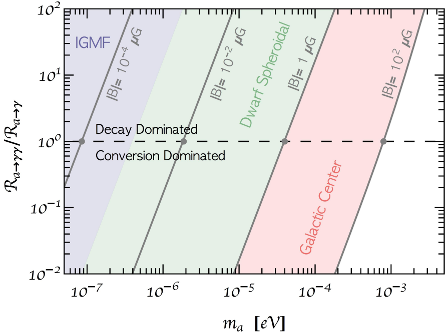
Spontaneous decay (1) — Stimulated emission ($2n_\gamma$)

Decay vs. Conversion

Lets make a naive comparison.

$$\frac{R_{a\to\gamma\gamma}}{R_{a\to\gamma}} \sim \frac{m_a^4}{64\pi B_0^2\, f_a(m_a)}\left(1+\frac{2}{e^{m_a/2T_{\rm cmb}}-1}\right) \tag{14}$$

Being ridiculous for a moment, we will take $f_a \sim 1$



Required Features for Radiotelescope

- Sensitive to frequencies in range $\mathcal{O}(100)$ MHz to $\mathcal{O}(100)$ GHz
  $\rightarrow$ sensitive to dark matter mass range

- Large number of channels
  $\rightarrow$ resolve narrow spectral line

- Larger field of view
  $\rightarrow$ maximize dark matter column density

$$\alpha_{\text{int}} \sim 8.8 \times \left(\frac{\text{GHz}}{\nu}\right)\left(\frac{1\text{m}}{D_{\text{dish}}}\right) \text{degrees} \qquad (15)$$

- Low system temperature and large effective area

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SKA-Mid

SKA-Mid (1) probes frequencies ~ 350 MHz – 20 GHz, (2) has $\mathcal{O}(kHz)$ sensitivity to spectral lines, (3) 13/15 m dishes, (4) phenomenal $A_{\rm eff}/T_{sys}$

Timeline

2024	Full operation
2020 - 24	Phase two construction
2020	Full science operations with phase one
2016 - 20	Phase one construction
2013 - 15	Detailed design and pre-construction phase
2012	Site selection
2008 - 12	Telescope conceptual design

https://www.skatelescope.org

Selecting a Target

- In general the photon number density will be difficult to model

$$n_\gamma(\vec{r}) \simeq n_{cmb} + n_{syn}(\vec{r}) + n_{\text{free}-\text{free}}(\vec{r}) + \cdots \quad (16)$$

→ As first-order test, lets focus on low-background environment such that $n_\gamma \sim n_{cmb}$ (generically true $\gtrsim 1$ GHz)

- Small FoV means target spans $\lesssim 1^\circ$ diameter
(Not necessarily bad to look at smaller or distant objects)
- Astrophysical input

$$S_{decay} = \frac{m_a^2\, g^2}{64\pi} [1 + 2n_{\gamma,cmb}] \frac{1}{\sigma_{disp}} \int d\Omega\, d\ell\, \rho_a(\Omega, \ell) \quad (17)$$

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Dwarf Spheroidals fit the bill

Targeting Dwarf Spheroidal Galaxies (dSphs)

Lessons Learned from Indirect WIMP Searches

- Some dSphs are *always* better targets
  $\Longrightarrow \alpha_{\text{int}}(m_a)$
- Higher efficiency can be achieved with a stacked analysis
  $\Longrightarrow$ Small FoV $\rightarrow$ no dSphs for free
- May exist strong uncertainties in astrophysical factor
  $\Longrightarrow$ We care about $\int \rho$ not $\int \rho^2$, many dSphs approx equivalent

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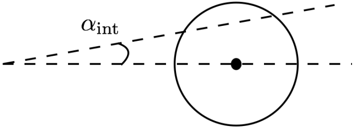

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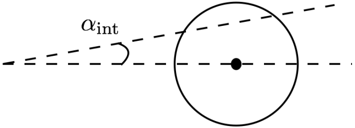

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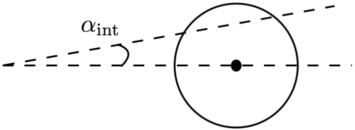

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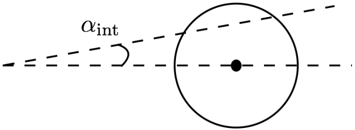

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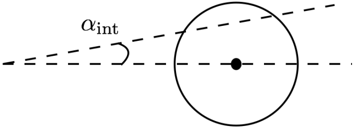
Targeting Dwarf Spheroidal Galaxies (dSphs)

Lessons Learned from Indirect WIMP Searches

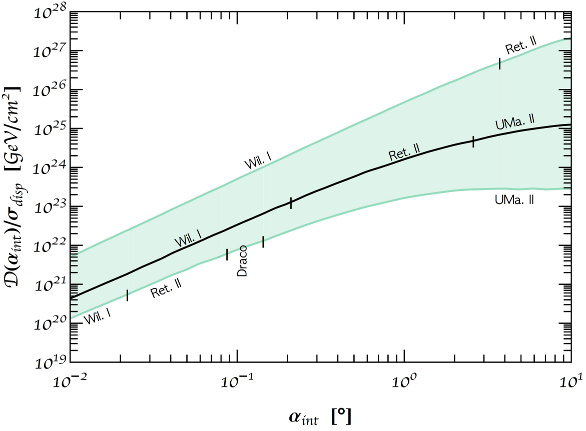
- Some dSphs are *always* better targets
  $\Longrightarrow \alpha_{\text{int}}(m_a)$



- Higher efficiency can be achieved with a stacked analysis
  $\Longrightarrow$ Small FoV $\rightarrow$ no dSphs for free
- May exist strong uncertainties in astrophysical factor
  $\Longrightarrow$ We care about $\int \rho$ not $\int \rho^2$, many dSphs approx equivalent

Selecting a Dwarf

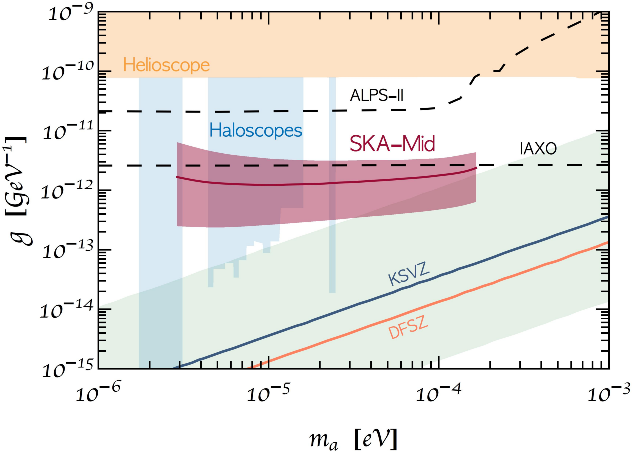
2018 Caputo, Peña-Garay, SJW



Astrophysical input inferred from kinematics:

see e.g. Geringer-Sameth et al (2015), Bonnivard et al (2015), Hayashi et al (2016)

SKA-Mid Sensitivity (100 hours)

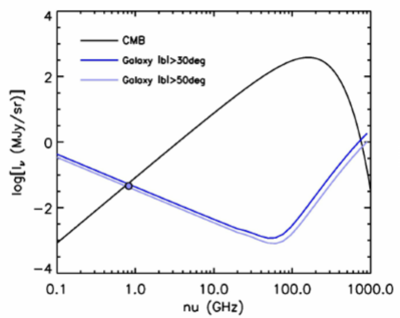


2018 Caputo, Peña-Garay, SJW

Outlook

- What prospects do other targets provide?
  - Enhanced ρ_a/σ in Galactic Center? Clusters?
    Caputo, Regis, Taoso, SJW (2018?)
  - Enhancement of stimulated emission from synchrotron and free-free?
    $\lesssim 1$ GHz CMB is subdominant

    Caputo, Regis, Taoso, SJW (2018?)



De Zotti et al 2016

Outlook

- Can we exploit existing radio telescope data?
  Miralda, Peña-Garay, Salvado, SJW (2018?)

- Prospects for other signatures, e.g. cross correlation PS
  Miralda, Peña-Garay, Salvado, SJW (2018?);
  See also Creque-Sarbinowski and Kamionkowski (2018) for HI mapping analysis

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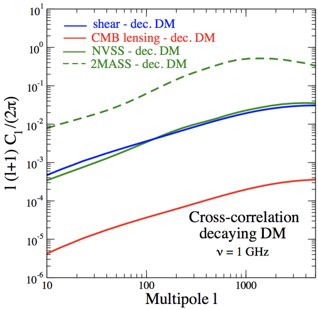

Fornengo and Regis (2014)

Summary

Take Home

- Radio telescopes ideally placed to probe expected mass range where QCD axion can account for entirety of dark matter
- On galactic scales, axion decay far more efficient than magnetic field conversion
- Complementary to direct axion searches (*e.g.* haloscopes) and indirect searches exploiting Primakoff effect

Looking forward

- What targets, signatures, telescopes, etc. offer the most promise
- Can we exploit stimulated emission in a clever way

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Thank you

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Additional Slides

$N_{DW} \neq 1$

For $N_{DW} > 1$ string-wall systems are stable, which produces conflict with cosmological observations

Y. B. Zeldovich, I. Y. Kobzarev and L. B. Okun (1974)

- Stability can be avoided by adding further interaction that explicitly break PQ symmetry (see *e.g.* Ringwald (2018) for brief discussion) These contributions may require tuning, as large terms may ruin solution to strong CP while small terms may lead to overclosure
- If $N_{DW} = 6, 9, 10$, the axion may provide correct abundance if

$$0.56\text{meV} \lesssim m_a \lesssim 130\text{meV} \tag{18}$$