# Astrophysical searches for the string axiverse

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Axions ++
LAPTh
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# Outline



2107.12813, FCD
23xx.xxxxx, FCD, James Maxwell and Jessica Turner

# Collaborators

Jessica Turner

James Maxwell

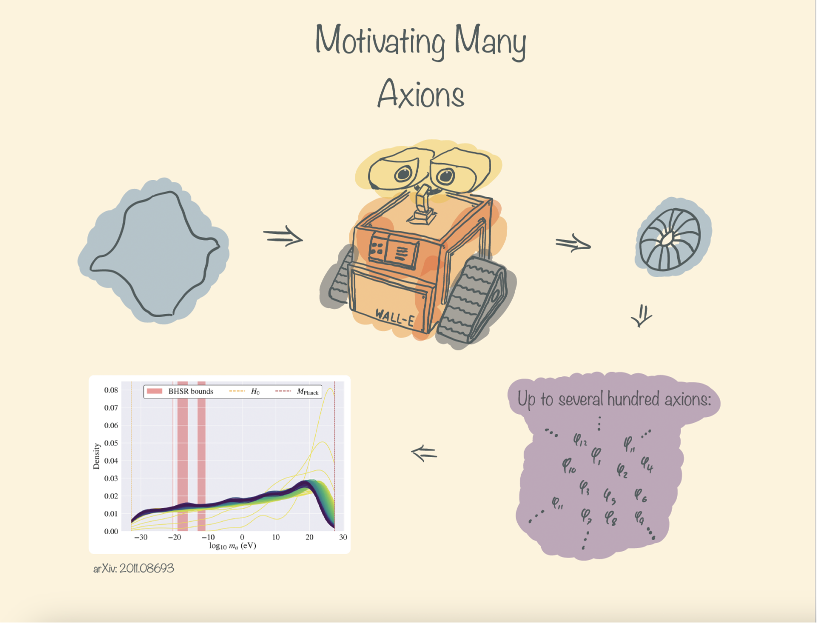
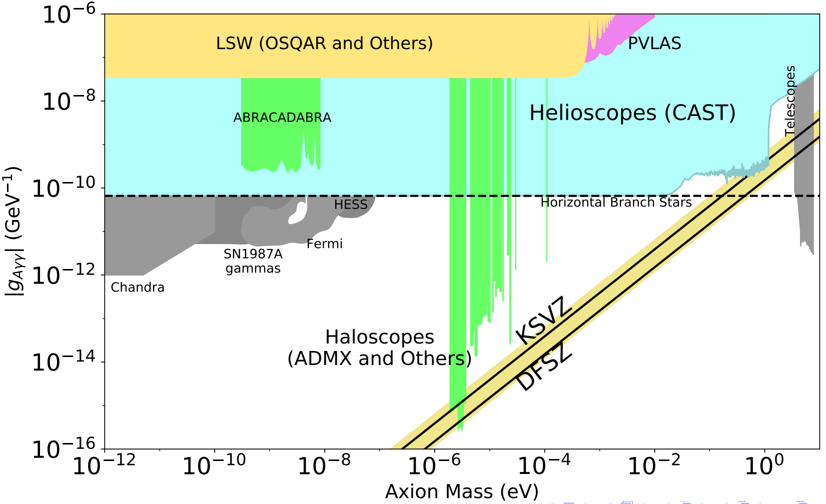



Image by James Maxwell

# Bounds on the ALP-photon interaction



# Axiverse signatures

- The string axiverse may lead to a complex, multi-component dark sector.
- Avoiding overproduction of string ALPs is a significant constraint (M. Stott *et al*, 1706.03236).
- Constraints on the axiverse mass spectrum from Black Hole superradiance (Stott & Marsh, 1805.02016; V. Mehta *et al*, 2103.06812)

# The ALP-photon Lagrangian

$$\mathcal{L} \supset \sum_i \left( -\frac{1}{2}\partial^\mu \phi^i \partial_\mu \phi^i - \frac{1}{2} m_i^2 (\phi^i)^2 - g_i^\gamma \phi^i \tilde{F}^{\mu\nu} F_{\mu\nu} \right)$$

# The ALP-photon Lagrangian

$$\mathcal{L} \supset \sum_i \left( \frac{1}{2}\partial^\mu \phi^i \partial_\mu \phi^i - \frac{1}{2} m_i^2 (\phi^i)^2 - g_i^\gamma \phi^i \tilde{F}^{\mu\nu} F_{\mu\nu} \right)$$

Change basis so that only one ALP couples to electromagnetism:

$$\phi^1 = \frac{\sum_i g_i^\gamma \phi^i}{\sqrt{\sum_i {g_i^\gamma}^2}}.$$

See Halverson *et al*, 1909.05257.

# The ALP-photon Lagrangian

$$\mathcal{L} \supset \sum_i \frac{1}{2}\partial^\mu \phi^i \partial_\mu \phi^i - \sum_{i,j} \frac{1}{2} M_{ij}\phi^i \phi^j - g^\gamma \phi^1 \tilde{F}^{\mu\nu} F_{\mu\nu}$$

As the mass matrix is not diagonal, we will see oscillations between $\phi^1$ and the other ALP fields.

# ALP-photon Oscillations

Transformation between mass and electromagnetic bases:

$$|\phi^i_{\mathrm{mass}}\rangle = U_{ji}\,|\phi^j_{\mathrm{EM}}\rangle \, ,$$

This leads to oscillations between the ALP fields akin to neutrino oscillations.

# ALP Oscillations

Electromagnetic ALP survival probability:

$$P_{1\to 1} = 1-4\sum_{i>j} |U_{1i}|^2 |U_{1j}|^2 \sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right),$$

where $\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$.

# The two ALP case

Only two ALP mass eigenstates couple to electromagnetism:

$$\mathcal{L} \supset \sum_i \left( \frac{1}{2} \partial^\mu \phi^i \partial_\mu \phi^i - \frac{1}{2} m_i^2 (\phi^i)^2 \right) - g_1^\gamma \phi^1 \tilde{F}^{\mu\nu} F_{\mu\nu} - g_2^\gamma \phi^2 \tilde{F}^{\mu\nu} F_{\mu\nu}$$

# The two ALP case

The mass basis and the electromagnetic basis are related by

$$\begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \phi_\gamma \\ \phi_h \end{pmatrix},$$

$$\theta = \cos^{-1}\left( \frac{g_1^\gamma}{\sqrt{{g_1^\gamma}^2 + {g_2^\gamma}^2}} \right).$$

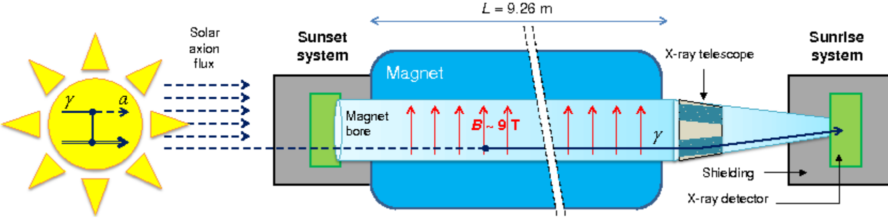
# The two ALP case

In the absence of a background magnetic field, the probability of an electromagnetic ALP oscillating into a hidden ALP is

$$P_{\phi_\gamma \to \phi_h} = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right),$$

where $\Delta m^2 = m_1^2 - m_2^2$, $L$ is the propagation length and $E$ is the ALP's energy.

# CAST




Reproduced from 1705.02290.

# CAST

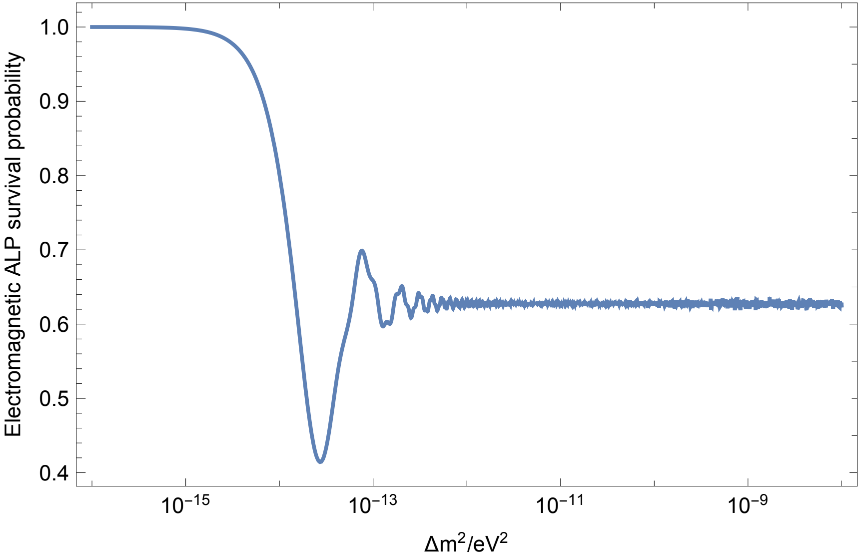
- Assume that $m_1$ and $m_2$ are both negligible.
- Primakoff production in the Sun produces the state $\phi_\gamma$.
- ALPs produced electromagnetically in the Sun may oscillate into hidden ALPs as they travel to Earth, and therefore be unobservable to CAST.

# CAST ALP spectrum

Average electromagnetic ALP survival probability over the sun's ALP spectrum:

$$P_{\phi_\gamma \to \phi_\gamma} = 1 - \sin^2 2\theta \frac{\int_{2\,\mathrm{keV}}^{7\,\mathrm{keV}} \sin^2\left(\frac{\Delta m^2 L}{4E}\right) \frac{d\Phi_a}{dE} dE}{\int_{2\,\mathrm{keV}}^{7\,\mathrm{keV}} \frac{d\Phi_a}{dE} dE}$$

# CAST



Electromagnetic ALP survival probability
1.0
0.9
0.8
0.7
0.6
0.5
0.4
$10^{-15}$
$10^{-13}$
$10^{-11}$
$10^{-9}$
$\Delta m^2/\mathrm{eV}^2$

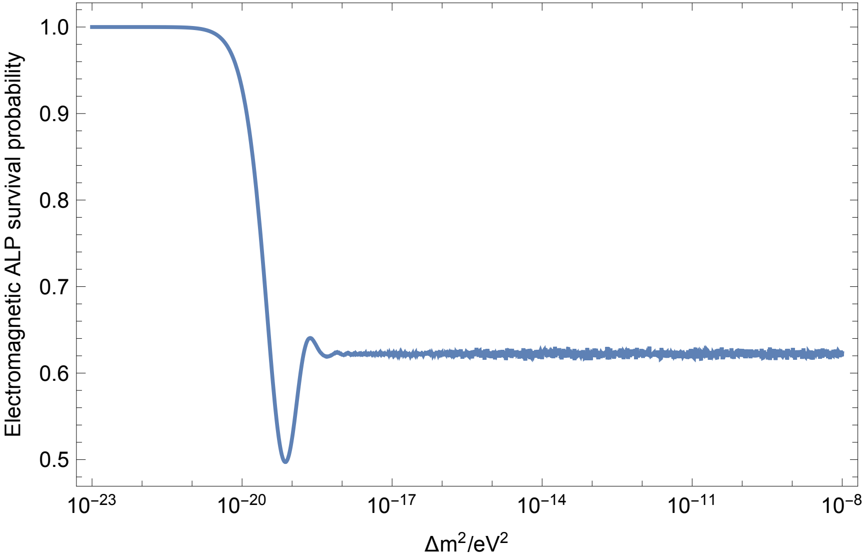
# ALP searches from SN1987A

- ALPs produced in SN1987A in the Large Magellanic Cloud
- Some of these ALPs convert to $\gamma$-rays in the Milky Way magnetic field
- Non-observation of these $\gamma$-rays allows us to place bounds on $g^{\gamma}$.
- See e.g. A. Payez *et al*, 1410.3747

# ALP searches from SN1987A

- Primakoff production in SN1987A produces the state $\phi_\gamma$.
- ALPs produced electromagnetically in SN1987A may oscillate into hidden ALPs as they travel to the Milky Way, and therefore be unavailable for conversion to $\gamma$-rays.
- Average over the SN1987A ALP spectrum.

# ALP searches from SN1987A



# Many ALP fields

What if many light ALP mass eigenstates have non-negligible coupling to electromagnetism?

In the electromagnetic basis, there will be many hidden ALP fields.

# Many ALP fields

Electromagnetic ALP survival probability:

$$P_{1\to 1} = 1 - 4\sum_{i>j} |U_{1i}|^2 |U_{1j}|^2 \sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right),$$

In the long $L$ limit for any given $\Delta m_{ij}^2$, $L \gg \frac{4E_0}{\Delta m_{ij}^2}$:

$$\frac{\int \sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right)\frac{d\Phi_a}{dE}dE}{\int \frac{d\Phi_a}{dE}dE} \sim \frac{1}{2},$$

where $\frac{d\Phi_a}{dE}$ is a general astrophysical ALP spectrum.

# Many ALP fields

In the long $L$ limit for *all* $\Delta m^2_{ij}$

$$P_{1\to 1} \sim 1 - 2\sum_{i>j} |U_{1i}U_{1j}|^2.$$

$U$ transforms between the electromagnetic and mass bases:

$$U_{1i} = \frac{g_i^\gamma}{\sqrt{\sum_i {g_i^\gamma}^2}}$$

# Many ALP fields

$$P_{1\to 1} \sim 1 - 2\sum_{i>j}\left|\frac{g_i^\gamma g_j^\gamma}{\sum_k g_k^{\gamma 2}}\right|^2$$

$$= 1 - 2\frac{\sum_{i>j}\left(g_i^\gamma g_j^\gamma\right)^2}{\sum_{i>j}\left(g_i^\gamma g_j^\gamma\right)^2 + \sum_{j>i}\left(g_i^\gamma g_j^\gamma\right)^2 + \sum_{i=j}\left(g_i^\gamma g_j^\gamma\right)^2}$$

$$\sim 0\,,\ \text{for very large number of ALP fields}$$

# Many ALP fields

Many ALP mass eigenstate fields coupling to electromagnetism

$\downarrow$

Electromagnetic ALP is a linear combination of many mass eigenstates

$\downarrow$

The electromagnetic ALP mixes with many hidden ALPs

$\downarrow$

Electromagnetic ALP survival probability is very low over large distances

# Summary

- String axiverse scenarios contain an ‘electromagnetic’ ALP and a number of ‘hidden’ ALPs.
- These ALPs undergo oscillations similar to neutrino oscillations.
- ALP oscillations may significantly reduce the experimental signals when an ALP is produced and then *travels a long distance* before being detected.

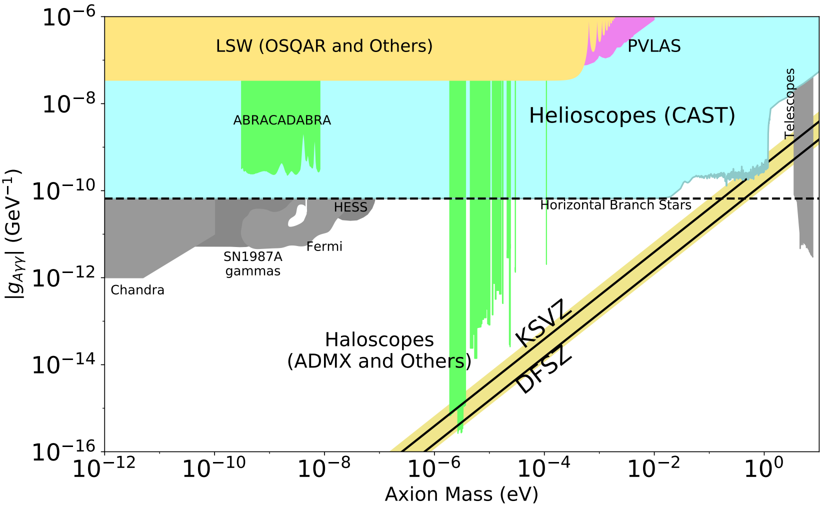
# Summary

- This may effect ALP bounds from CAST and from SN1987A.
- Effects that only probe ALP production (e.g. stellar cooling) are not significantly affected by ALP oscillations.
- This work does not apply to the QCD axion, which gets a mass and coupling to electromagnetism from QCD effects.

# Discussion

- Comparisons between different ALP search strategies become harder.
- This effect could reconcile the possible observation of ALP induced modulations in galactic pulsar spectra (Majumdar, Calore & Horns, 1801.08813) with the bounds on $g^{\gamma}$ from CAST and from SN1987A - but not from stellar cooling bounds.

# Discussion


LSW (OSQAR and Others)
PVLAS
ABRACADABRA
Helioscopes (CAST)
Telescopes
HESS
Horizontal Branch Stars
Fermi
SN1987A
gammas
Chandra
KSVZ
DFSZ
Haloscopes
(ADMX and Others)
$|g_{A\gamma\gamma}|$ (GeV$^{-1}$)
Axion Mass (eV)
$10^{-6}$
$10^{-8}$
$10^{-10}$
$10^{-12}$
$10^{-14}$
$10^{-16}$
$10^{-12}$
$10^{-10}$
$10^{-8}$
$10^{-6}$
$10^{-4}$
$10^{-2}$
$10^{0}$

# Discussion

- The effect of oscillations could be very large when many ALP mass eignstates couple to electromagnetism.
- A similar mechanism will operate with other ALP couplings (see 23xx.xxxxx, FCD, James Maxwell and Jessica Turner).
- String axiverse phenomenology is very rich and warrants further study.