Axion electrodynamics

Marc Steiner, 18.05.2020

Overview

- What is an axion
  - Strong CP problem
  - Peccei–Quinn mechanism
  - The axion field
- Axion electrodynamics
- Cosmological considerations
- Experiments

What is an axion

According to Wikipedia:

> The axion is a hypothetical elementary particle postulated by the Peccei–Quinn theory to resolve the strong CP problem in quantum chromodynamics (QCD).

Why are axions interesting?

> If axions exist and have low mass within a specific range, they are of interest as a possible component of cold dark matter.

CP symmetry

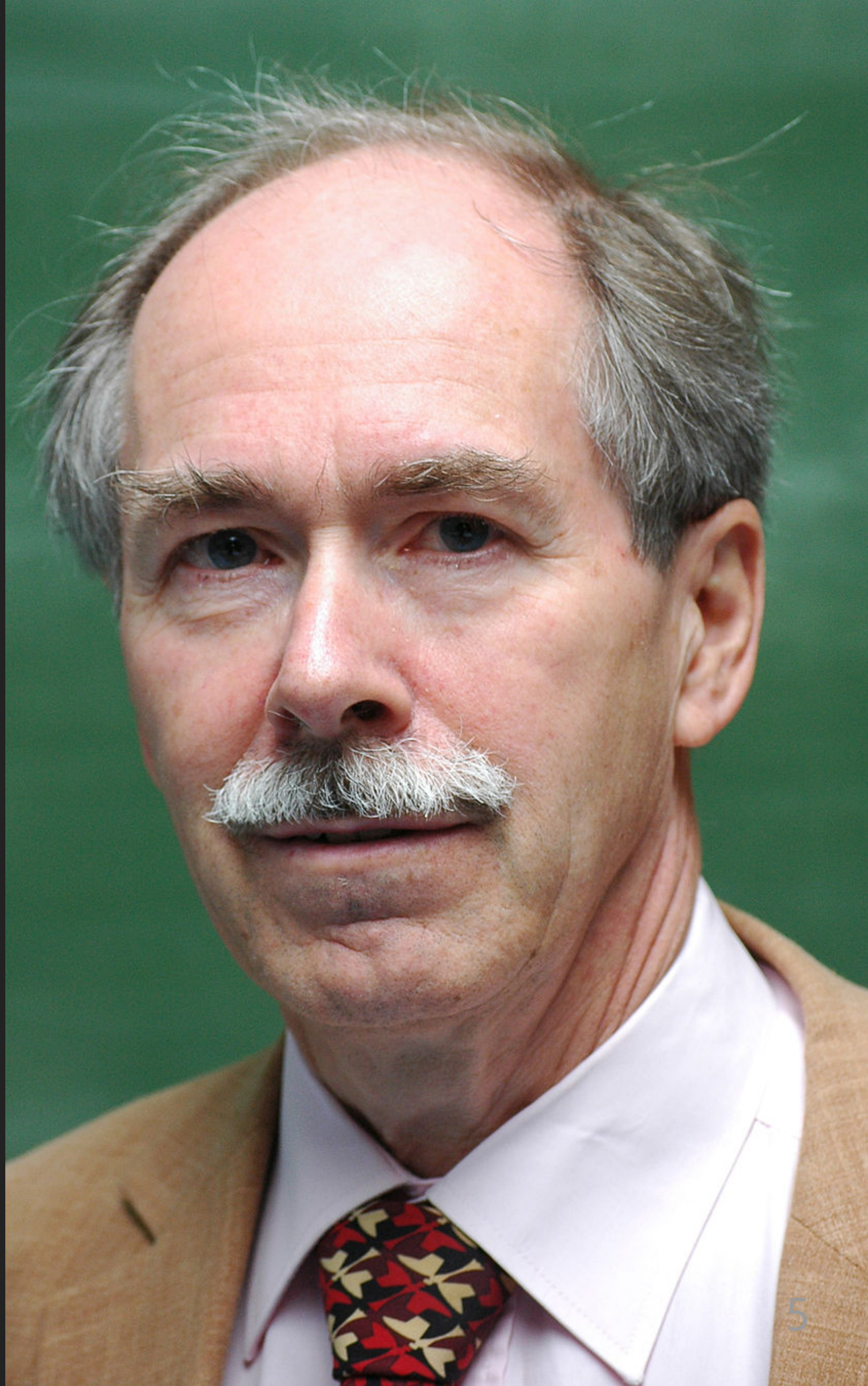
> CP-symmetry states that the laws of physics should be the same if a particle were interchanged with its antiparticle (C symmetry, as charges of antiparticles are the negative of the corresponding particle), and then left and right were swapped (P symmetry).

Strong CP problem

$$\mathcal{L}_{\text{QCD}} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \theta \frac{n_f g^2}{32\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu} + \bar{\psi}(i\gamma^\mu D_\mu - m e^{i\theta' \gamma_5})\psi$$

Contains a CP symmetry violating term:

$$L_\theta = \theta \frac{n_f g^2}{32\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu}$$



Strong CP problem

Neutron electric dipole moment

- CP symmetry violation leads to a electric dipole moment for the neutron
- So far not measured and can only be very tiny
- Therefore CP violation and θ has to be tiny as well ($< 10^{-10}\ rad$)
- Poses a "naturalness" problem
- Natural theories have free parameters (θ in QCD) of the order 1
- θ should be ≈ 1 and not $\approx 10^{-10}$

Strong CP problem

Massless quarks

- Even one massless quark type would render CP violation unobservable
- However empirical evidence strongly suggest that none of the quarks are massless
- Other explanations?

Peccei–Quinn mechanism

- Postulated by Helen Quinn and Roberto Peccei
- Promote the θ parameter to a dynamic field
- The potential of this field cancels its value
- θ becomes zero uneventfully, naturally resolving the strong CP problem

The axion field

- Th symmetry introduced by Quinn and Peccei is spontaneously broken by the vacuum expectation value of θ
- The axion arises as massless Nambu-Goldstone boson of this broken symmetry according to Goldstone's theorem
- First postulated independently by Frank Wilczek and Steven Weinberg
- Named by Frank Wilczek after the laundry detergent axion

The axion field

$$L_\theta = \theta \frac{n_f g^2}{32\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu} \implies L_a = \frac{a}{f_a} \frac{n_f g^2}{32\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Possible axion models

- Original Wilczek/Weinberg axion ruled out
- Properties depend on the vacuum expectation value f_a of θ
- Axion mass and its coupling are inversely proportional to f_a
- f_a can be arbitrary with regard to resolving the strong CP problem
- From experiments and theoretical considerations: $f_a > 10^8 GeV$
- Axions have been called "invisible"

Axion

- Symbol: A^0
- No electric charge and no spin
- Mass between 10^{-5} to $10^{-3}\ \frac{eV}{c^2}$
- Interacts only gravitationally and electromagnetically
- Very weak interaction
- Good candidate for dark matter, due to its mass and weak interaction

Axion electrodynamics

- Pierre Sikivie postulated a modification of Maxwell's equations including the interaction with axions
- Proposed multiple experiments to measure them
- All rely on axion ⇔ photon conversion in the presence of strong magnetic fields

Axion electrodynamics

Modified Maxwell's equations

Name	Equation
Gauss' law	$\nabla \cdot (\mathbf{E} - \kappa\theta c\mathbf{B}) = \frac{\rho_e}{\varepsilon_0}$
Gauss's law for magnetism	$\nabla \cdot (c\mathbf{B} + \kappa\theta\mathbf{E}) = 0$
Faraday's law	$\nabla \times (\mathbf{E} - \kappa\theta c\mathbf{B}) = -\partial_{ct}(c\mathbf{B} + \kappa\theta\mathbf{E})$
Ampère's law	$\nabla \times (c\mathbf{B} + \kappa\theta\mathbf{E}) = \partial_{ct}(\mathbf{E} - \kappa\theta c\mathbf{B}) + c\mu_0\mathbf{J}_e$
Axion law	$(\Box + m_a^2)\theta = -\kappa\mathbf{E} \cdot \mathbf{B}$

Axion electrodynamics

Rotating $\mathbf{E}$ and $\mathbf{B}$ into one another

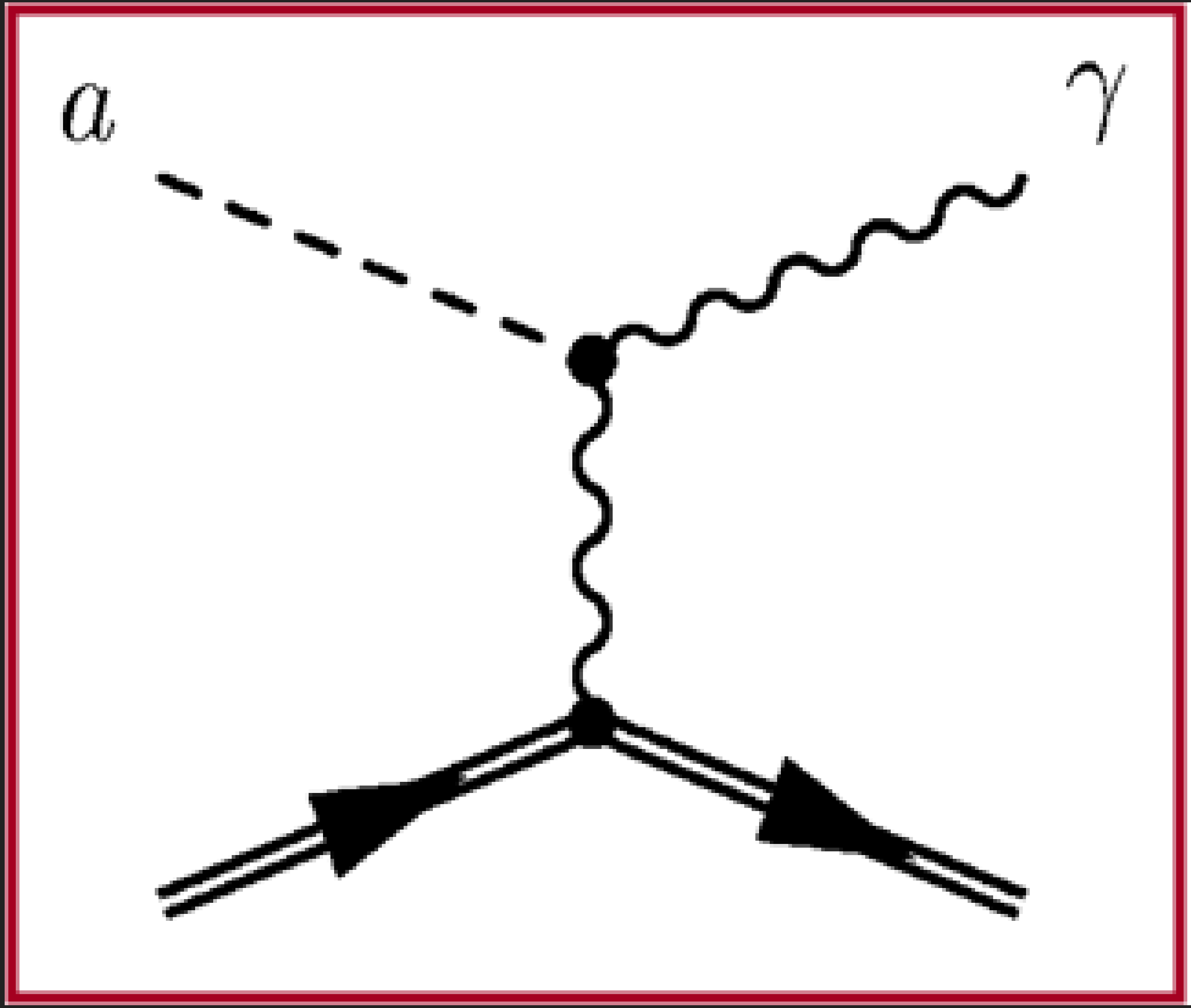
$$\begin{bmatrix} \mathbf{E}' \\ c\mathbf{B}' \end{bmatrix} = \frac{1}{\cos\xi} \begin{bmatrix} \cos\xi & \sin\xi \\ -\sin\xi & \cos\xi \end{bmatrix} \begin{bmatrix} \mathbf{E} \\ c\mathbf{B} \end{bmatrix}$$

with

$$\tan\xi = \tan(-\kappa\theta)$$

Axion electrodynamics

Photon $\Leftrightarrow$ Axion conversion



Cosmological considerations

- Axions might have played a critical role in galaxy formation, through axionic domain walls
- Axions might be dark matter halos around galaxies
- Axions might be created by the Primakoff effect
- Axions might be produced inside the sun

Experiments

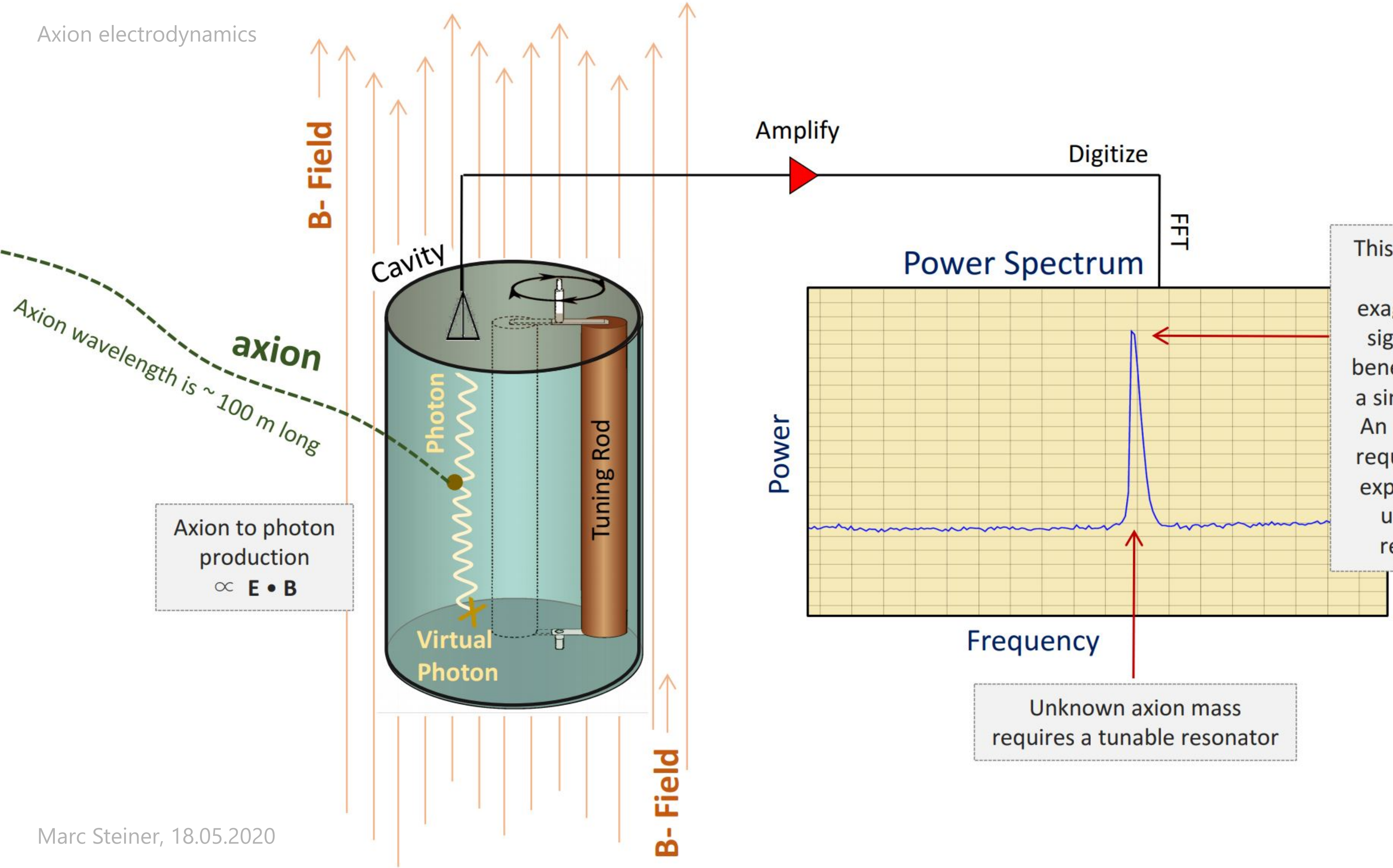
Sikivie proposed essentially two types of possible experiments:

- The axion haloscope
- The axion helioscope

Experiments

The axion haloscope

- Way to measure axions coming from the dark matter halo around our local galaxy
- Microwave cavity has to be resonantly tuned to the mass of the axion
- Dynamical cavity length to probe for different possible masses
- Noise reduction is important
- The magnetic field has to be inhomogeneous
- Inhomogeneity can be achieved by embedding wires of a superconducting metal in a material transparent to microwave radiation and cooling down to the critical temperature



Axion to photon production $\propto$ **E • B**

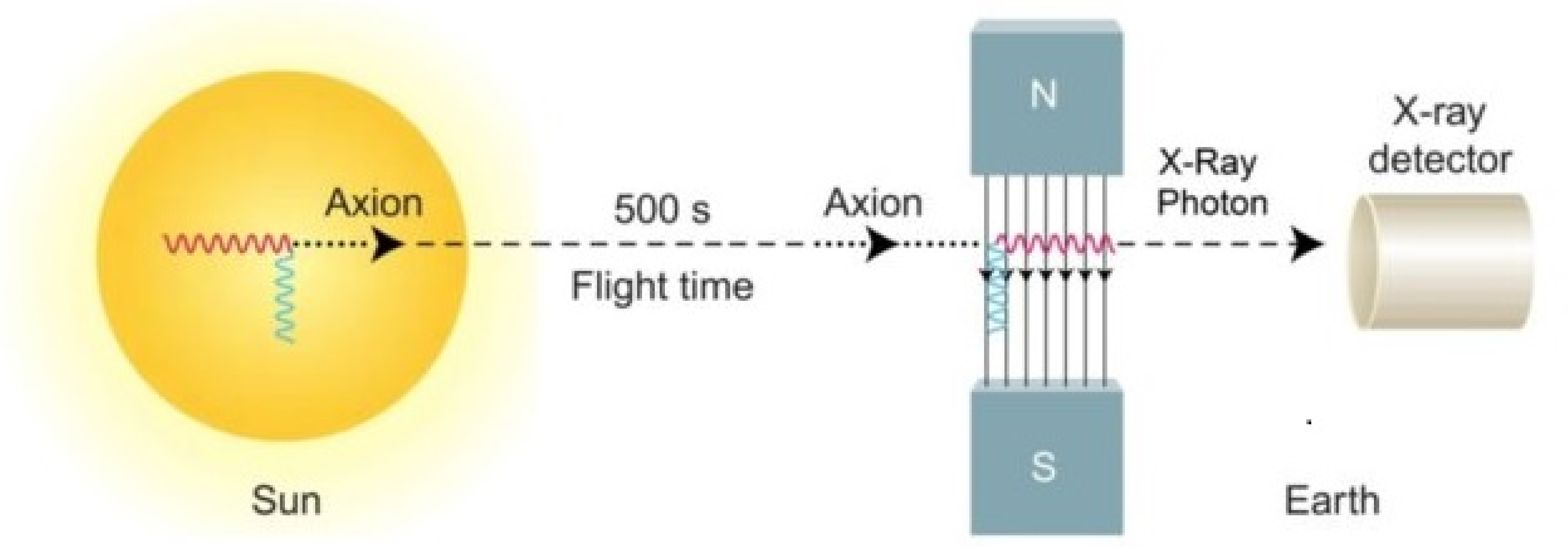
This axion lineshape has been exaggerated. A real signal would hide beneath the noise in a single digitization. An axion detection requires a very cold experiment and an ultra low noise receiver-chain.

Unknown axion mass requires a tunable resonator

Experiments

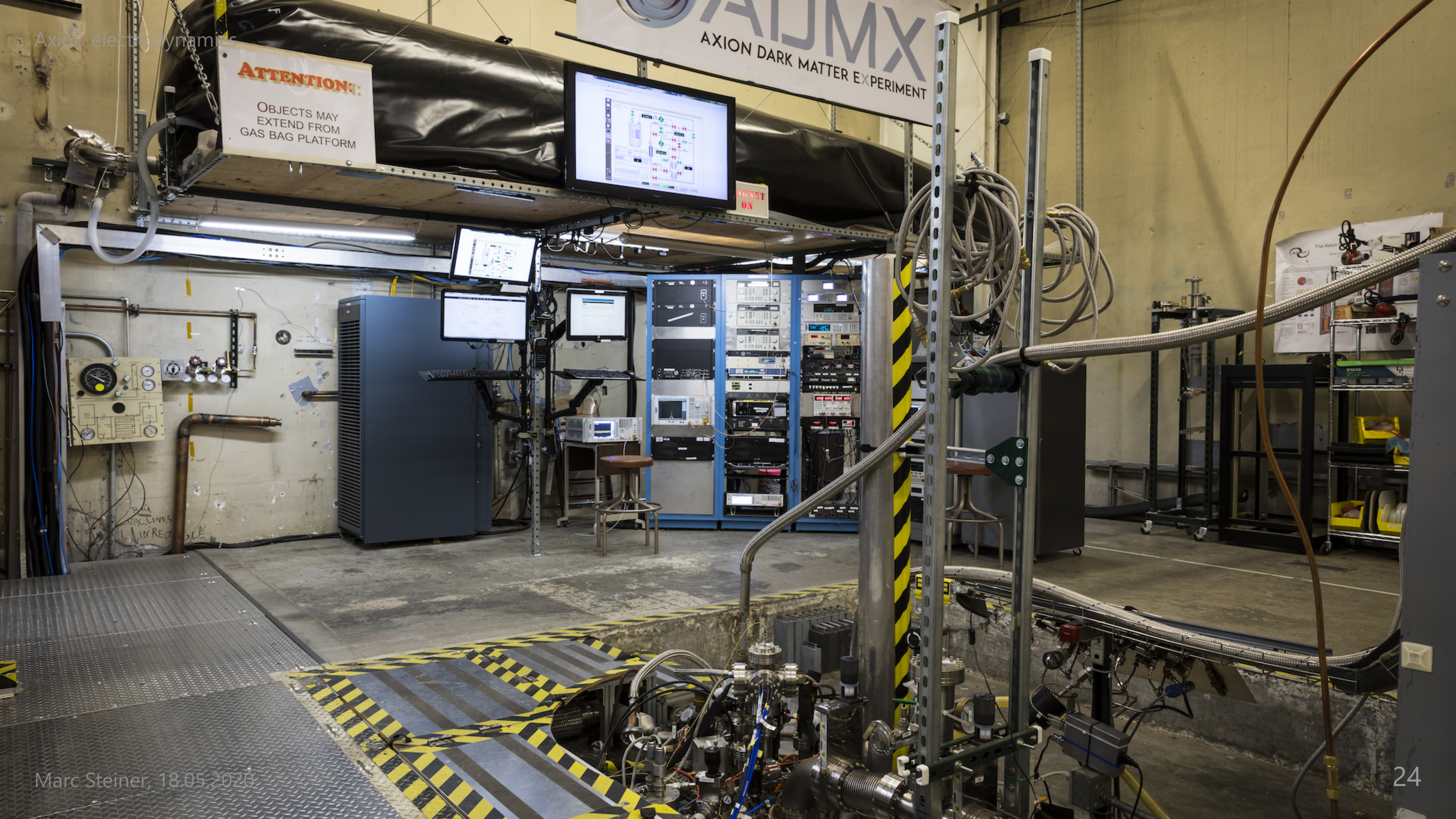
The axion helioscope

- Same principle as the haloscope but for solar axions
- Solar axions are expected to be produced in the sun due to the Primakoff effect
- Solar axions convert to X-rays in the presence of strong magnetic fields


Axion
500 s
Flight time
Axion
N
S
X-Ray
Photon
X-ray
detector
Sun
Earth

Current experiments

- Axion Dark Matter Experiment (ADMX)
  - Haloscope
  - Sited at the CENPA at the University of Washington
  - Large collaborative effort
- CERN Axion Solar Telescope (CAST)
  - Helioscope
  - Sited at CERN in Switzerland
- The International Axion Observatory (IAXO)
  - Successor to CAST
- Other experiments like PLVAS that build on other theoretical hypotheses


AXION DARK MATTER EXPERIMENT
ATTENTION:
OBJECTS MAY EXTEND FROM GAS BAG PLATFORM

Summary

- The axion is a hypothetical particle that appears as a solution to the strong CP problem, namely the Peccei-Quinn mechanism
- It is neutral and very light (but not massless)
- It interacts only very weakly with conventional matter
- It could transform into a photon (and viceversa) in the presence of a magnetic field (Axion electrodynamics)
- Excitingly, it could also be a very natural solution to the problem of dark matter, essentially killing two birds with one stone

Further readings

The Strong CP Problem and Axions (R. D. Peccei):
http://arxiv.org/pdf/hep-ph/0607268.pdf

QCD, Strong CP and Axions (R. D. Peccei):
https://cds.cern.ch/record/306320/files/9606475.pdf

Experimental Tests of the "Invisible" Axion (P. Sikivie):
https://sci-hub.tw/10.1103/physrevlett.51.1415

Symmetries in physics (N. Beisert):
http://edu.itp.phys.ethz.ch/hs15/sym/SymHS15Notes.pdf

Symmetry and symmetry breaking in particle physics (Tsou Sheung Tsun):
https://cds.cern.ch/record/349544/files/9803159.pdf