Goals (Lecture 4)

- Outline searches for dark matter and dark sectors at accelerators
  - searches at the LHC
  - searches in lower-energy accelerators
  - searches for dark sector particles
- Outline the cosmology of the cold dark matter axion
- Summarize current searches for axions and other ultralight/wave-like DM candidates
Accelerator searches
LHC searches in a nutshell

- If DM is produced at the LHC, it is stable => will escape the detector
- Cannot be detected directly, but will show up as missing energy/momentum
- Most direct DM searches at LHC are “mono-X” searches - look for visible particle recoiling off invisible partner
  - e.g. mono-Higgs
  - mono-jet
  - mono-photon
- Doesn’t fundamentally need to be “mono” - could be more than one visible particle/jet in the event

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Approaches for dark matter

• Construct detailed model of high-energy physics (e.g. SUSY model), search for resulting signatures
  • Upside: since there are many non-DM particles, can have striking effects. Characteristic signatures can include cascades producing many particles, with large “MET” (missing momentum transverse to the beam direction) - since all SUSY partners decay to the LSP eventually
  • Downside: not easy to translate constraints on one model into bounds on another model. (Not “model-independent”.) Makes interpretation more challenging.

• Construct simplified model with only a few ingredients, develop generic searches
  • Upside: easy to translate to many models, reduces the risk of missing a signal due to searching too narrowly
  • Downside: sometimes effects of extra ingredients are important! No guarantee that simplified model can be embedded into reasonable high-energy theory.

• Approaches are complementary.

• Can also use effective field theory approach if heavy degrees of freedom can self-consistently be integrated out (not always the case).
Example of a simplified model approach: suppose DM couples to some heavy mediator, which also couples to quarks.

Exchange of this mediator allows pair production of DM, along with other particles.

Can consider different possibilities for the spin of the mediator - vector, axial vector, scalar, pseudoscalar, etc.
Other accelerator searches

- For light DM or DM that interacts with the SM through new light weakly-coupled particles, high luminosity may be more important than high energy.

- Active program of fixed-target and collider experiments to search for both DM annihilating through new mediators + new mediators themselves.

- Immediate target: “full exploration of the range of interaction strengths compatible with light DM thermal freeze-out via the simplest mechanism of s-channel annihilation to SM particles mediated by a dark photon.”

- Gori et al ‘22 (Snowmass, RF6 topical report) provides an in-depth discussion.
Thermal relic targets

- General argument: direct/indirect detection largely measure DM interactions in the present-day halo, $v \sim 10^{-3}$

- Accelerators allow reproduction of conditions in the freezeout epoch (relativistic or near-relativistic DM)

- Leads to relatively narrow range of expected accelerator signals for simple portal models with thermal freezeout

- Multiple channels to probe DM production

Gori et al '22 (Snowmass)
Dark sector searches

- Mediators coupled to the SM through minimal portals could exist whether or not they relate to DM
- In some cases, may be our first clue to the existence of a dark sector
- Mediators can decay to SM particles or invisibly into the dark sector - can search for both
- Can use existing accelerators (including the LHC) as a source of long-lived particles - search for their displaced decays with additional detectors (e.g. FASER, CODEX-b, MATHUSLA)

Example: status of Higgs portal with visible decays
Axions
Wave-like DM

• For mass scales below $\sim 1$ keV, DM must be both **bosonic** and **avoid thermal contact** with the SM

• Stable light bosons that are sufficiently cold can be good DM candidates down to masses of $10^{-21}$ eV: enormous range of possibilities

• Typically the DM abundance is not fixed through SM interactions

• Classic example is the **QCD axion**
The strong CP problem

- The Standard Model Lagrangian, describing all known particle interactions, in principle should have a term of the form:
  \[ \mathcal{L}_\theta = \frac{\theta}{16\pi^2} G_{\mu\nu} \tilde{G}^{\mu\nu} \]  
  gluon field strength
- A term like this can be generated by CP violation elsewhere in the Standard Model, in the terms describing the quarks - no reason for it to vanish.
- But this term induces a neutron electric dipole moment:
  \[ d_n = 5.2 \times 10^{-16} \text{ e cm} \]
- Experimentally, we know that:
  \[ d_n < 3 \times 10^{-26} \text{ e cm} \quad \Rightarrow \quad \theta \lesssim 10^{-10} \]
- Why is this value so small?
The axion proposal

• Replace the parameter $\Theta$ by a dynamical field, call it (by convention) $a/f_a$ where $a$ is the field and $1/f_a$ a coupling.

• Now we just need to explain why $a$ would evolve toward a very small value.

• But the energy stored in this field depends on the value of $a$ - potential energy changes as $a$ evolves.

• We can work out this effective potential (I won’t give the calculation here - see e.g. Dine’s TASI lectures hep-ph/0011376 for much more detail on the strong CP problem) and find:

$$V(a) = -m_{\pi}^2 f_{\pi}^2 \frac{\sqrt{m_u m_d}}{m_u + m_d} \cos(a/f_a)$$

$$f_{\pi} \approx 93\text{MeV}$$

$$m_{\pi} \approx 135\text{MeV}$$
The axion potential

- Field should evolve toward small values of this potential.
- Minima occur at $a/f_a = 2n\pi$; let’s look at $n=0$.
- The potential is parabolic - coefficient of $a^2$ term gives axion mass.

\[
V(a) = m_\pi^2 f_\pi^2 \frac{\sqrt{m_u m_d}}{m_u + m_d} + \frac{1}{2} a^2 \left( \frac{f_\pi}{f_a} \right)^2 m_\pi^2 \frac{\sqrt{m_u m_d}}{m_u + m_d} + O(a^4)
\]

\[
m_a = \frac{f_\pi m_\pi}{f_a} \left( \frac{m_u m_d}{(m_u + m_d)^2} \right)^{1/4} \approx 0.6\text{meV} \left( \frac{10^{10}\text{GeV}}{f_a} \right)
\]
**Axion properties**

- Axion coupling to Standard Model fields is controlled by the coupling $f_a$, although exact couplings depend on details of model.
  - “DFSZ axion” - axion couples to photons, gluons, leptons, quarks
  - “KSVZ axion / hadronic axion” - axion couples to photons and gluons, but at lowest order no coupling to leptons or light quarks
- Axion mass is inversely proportional to their coupling to Standard Model fields - weakly coupled axions can be very light.
- One might think this makes them poor DM candidates - too hot?
Thermal axions

- Coupling for axions can be very weak
- In contrast to WIMPs, question is not “when did they fall out of equilibrium” but “were they ever in equilibrium”?
- Axions produced in early universe by interactions of photons, pions
- Axions can also decay - and are produced singly, not in pairs (no symmetry keeping them stable)
- Need to check lifetime is $>>$ age of universe
- Solve Boltzmann equation including decay + all production processes
Thermal axions as hot dark matter

• Timescale for decay to photons is approximately given by:

\[ \tau \sim 10^{24} \text{s} \left( \frac{m_A}{\text{eV}} \right)^{-5} \]

• Age of universe \( \sim 10^{10} \text{yr} \sim \pi \times 10^{17} \text{s} \) \( \Rightarrow \) for axions to be around today, must be lighter than \( \sim 20 \text{ eV} \) (unless decay suppressed in specific model)

• Side note: at axion masses between about 20 eV and 300 keV, the photons from this process would disrupt nucleosynthesis!

• Solving Boltzmann equation, axions could attain thermal equilibrium if \( m_a > 10^{-3}-10^{-2} \text{ eV} \)

• In this case, very roughly, fraction of critical density in axions:

\[ \Omega_{\text{axions}} \sim \mathcal{O} \left( \frac{m_a}{100 \text{eV}} \right) \]

hot dark matter - needs to be small fraction of total DM

\[ m_a < 1 \text{ eV} \text{ is OK} \]
Non-thermal axions as cold dark matter

- But what if axions never equilibrate with SM?
- Sufficiently cold, light axions behave like a classical scalar field, evolving in axion potential - not individual particles

Q: How does the field evolve?

A: If initially displaced from minimum of potential (by some "misalignment angle"), must “roll” toward that minimum

[Diagram showing stable and unstable configurations]
An evolving scalar field

\[ \frac{d^2 \tilde{a}}{dt^2} + 3H \frac{d\tilde{a}}{dt} + m_a^2 \tilde{a} = 0 \]

equations of motion for scalar field in FRW

describes shape of potential near minimum

- For \( m_a \ll H \), approximate solution with \( da/dt = 0 \) - field does not evolve
- For \( m_a > H \), field begins to oscillate in potential - like simple harmonic oscillator with \( H \)-dependent friction term ("Hubble friction"). For large \( t \) solution has approximate form:

\[ \tilde{a}(t) = \Theta_0 f(t) \cos(m_a t) \]

\( f(t) \) slowly varying compared to oscillations, normalized so \( f(t_0)\cos(m_a t_0) = 1 \)

misalignment parameter

- Solving for \( f(t) \) we find that \( f(t) \) scales like \( a^{-3/2} \).

\[
-2f'(t)m_a \sin(m_a t) - 3Hm_a f(t) \sin(m_a t) = 0
\]

\[
\frac{1}{f} \frac{df}{dt} = -(3/2) \frac{1}{a} \frac{da}{dt}
\]
Energy density in the axion field

- The energy density has both kinetic and potential components,

\[ \rho = \frac{1}{2} m_a^2 \ddot{a}^2 + \frac{1}{2} \dot{a}^2 = \frac{1}{2} f(t)^2 \Theta_0^2 m_a^2 (\cos^2(m_a t) + \sin^2(m_a t)) = \frac{1}{2} f(t)^2 m_a^2 \Theta_0^2 \]

- The energy density does not oscillate rapidly, but decays as \( f^2 \sim a^{-3} \), as required for cold dark matter.

- Convenient to write \( \Theta_0 = \theta f_a \); then \( \theta \) is a dimensionless angle that can take values between 0 and \( \pi \).

- Initial energy density stored in the field at start of oscillations is \( \rho = (1/2) m_a^2 f_a^2 \Theta_0^2 \)

- The late-time density is thus set by the initial misalignment angle \( \theta \), and by when the field starts oscillating due to \( m_a \sim H \).

- For the QCD axion, \( m_a \) is \( T \)-dependent and does not turn on until during the QCD phase transition, needs a careful calculation.
Axions and inflation

- What value should we expect the misalignment angle to take?
- If axions are produced / misalignment angle is set only after inflation, i.e. H_I >> f_a, different patches of cosmos likely have different misalignment angles - take average of random sample
- If misalignment angle is set (in patches) before inflation, each such patch gets blown up at inflation - everywhere in our Hubble volume should have same angle
  - “anthropic axion”?

There are stringent constraints on scenarios where axion is all the DM and the energy scale of inflation is high - see Hertzberg, Tegmark & Wilczek ‘08
Learning about inflation may tell us about axions! (or vice versa)
Axion relic density

• Critical density in uniform-\(\theta\) case (for QCD axion):

\[ \Omega_{\text{axions}} = \Omega_{\text{DM}} \theta^2 \left( \frac{6\mu\text{eV}}{m_a} \right)^{1.165} \]

PDG review on axions, 2018

• Note that very light DM can require very small values of \(\theta\) - fine-tuned?

• On the other hand, \(\theta^2\) cannot be larger than \(O(10)\) - this mechanism requires \(m_a \sim 0.1\) meV or smaller (for the QCD axion).

• In the post-inflation case the calculation is more complicated as the non-uniform \(\theta\) leads to an axion string network, and domain walls, that decay to produce more DM axion energy density.

• This calculation is numerically difficult due to the large hierarchy of scales involved.
Axion relic density II

- If the contribution from axion strings is negligible, the favored QCD axion mass (in this post-inflation case) is $\sim 25 \, \mu\text{eV}$
- Different simulations have found different levels of contribution from the string network, resulting in preferred masses ranging from this lower bound to $\sim 500 \, \mu\text{eV}$
- Recent simulations using adaptive mesh refinement infer a scale-invariant spectrum for energy radiated by axion strings, and a preferred mass scale of $\sim 40-180 \, \mu\text{eV}$ [Buschmann et al '22]
Axion searches

- Most axion searches rely on the idea that in the presence of a magnetic field, an axion can convert into a photon (or vice versa)

- This means:
  - photons can convert into axions (and then back), e.g. allowing travel through regions that would otherwise be opaque
  - it might be possible to “catch” cosmological axions using magnetic fields, turning them into visible photons / inducing electromagnetic fields
  - Axions and axion-like particles could also induce nuclear electric dipole moments [Budker et al '14, CASPer experiment], modify the proton-neutron mass splitting and so affect nucleosynthesis [Blum et al '14], and otherwise have interesting QCD effects.

$$G_{a\gamma\gamma}aF^{\mu\nu}\tilde{F}_{\mu\nu} = G_{a\gamma\gamma}a\vec{E} \cdot \vec{B}$$
Some axion probes

- photons can travel through regions that should be opaque to them, by converting into axions and then back
  - high-energy photons traveling from high redshifts - would normally pair-produce on extragalactic background light, rendering the universe opaque - has been suggested as a mechanism to explain apparent very-high energy photons from recent bright gamma-ray burst [e.g. Carenza et al '22]
  - “light shining through a wall” (see e.g. Arias et al ’10 and references therein)
  - stellar cooling - axions escape more easily than photons [e.g. Isern et al ’08, Dessert et al ‘19]
  - photons passing through Galactic or cluster-scale magnetic fields can be distorted in intensity or polarization due to such conversions [e.g. Majumdar et al ’18, Schallmoser et al ’22]
- it might be possible to “catch” cosmological axions using magnetic fields, turning them into visible photons / inducing electromagnetic fields
  - Axion direct detection experiments (next few slides)
    - CAST - using the magnetic field of the Sun, searching for X-rays from conversion [e.g. Anastassopoulos et al ’17]. Next-gen version is IAXO.
    - Searches for radio emission from neutron star magnetospheres [e.g. Hook et al ’18].
    - Stimulated emission of photons from halo axions by an external bright source [e.g. Buen-Abad et al ’22, Sun et al ’22]
The Axion Dark Matter Experiment

- Idea: build a resonant microwave cavity containing a strong magnetic field
- Measure output power from cavity
- The axion-photon conversion will only occur if the frequency of the magnetic field matches with the axion energy (i.e. axion mass - DM axions are very cold)
- Vary cavity frequency, look for a bump in power. Detection would also measure axion mass.
- The ADMX Collaboration has tested the QCD axion for the mass ranges 2.66-2.81 μeV (2018), 2.81-3.31 (2020), 3.3-4.2 μeV (2021).

Note: hypothetical!
DMRadio

- Idea: in the limit where the axion Compton wavelength is significantly larger than the experiment, can treat effect of axion-photon interaction as a simple modification to Maxwell’s equations.

- Time oscillation of axion field (in 2nd term) sources oscillating effective current, which in turn sources small oscillating B-field.

- Couple this to a LC circuit for detection, with resonant frequency tuned to near the axion mass (scan resonant frequency to scan axion masses).

- See Benabou et al ’22 for a discussion of validity of magnetoquasistatic approximation, which simplifies equations by ignoring variations in effective axion-induced fields across the experiment.
Limits and forecasts

- Yellow line = QCD axion (width of band = DFSZ vs KSVZ)
- Remainder of parameter space = ALPs, “axion-like particles”
- In lower plot, red=targeting axion-photon coupling, blue=targeting other couplings
- Flagships for QCD axion in immediate future are ADMX-EFR, DMRadio-m³, but many other concepts: see https://cajohare.github.io/AxionLimits/ for updated limits/projections

Jaeckel et al ’22 (Snowmass)
Beyond the QCD axion

- Light bosonic DM is a plausible possibility whether or not it relates to the strong CP problem.
- Scalar/vector portals discussed earlier can apply to the DM candidate directly (as opposed to mediators).
- As well as misalignment, production mechanisms include decays of heavier states and topological configurations, & inflationary and gravitational production.
- Wide range of precision tests with sensitivity to such particles (see Jaeckel et al ’22 (Snowmass) & references therein).