Exploring the Dark Matter
ALPS

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Standard

ALP Dark Matter
What are ALPs?

- Axion-like particles
- Very light (sub-eV) bosons
- Very weakly coupled
- Often: Pseudo-Goldstone bosons
  (arising from spontaneous symmetry breaking at scale $f_a$)
Potential and mass related to SSB scale

- **Potential for Pseudo-Goldstones:**
  \[ V(\phi) = \Lambda^4 \left[ 1 - \cos \left( \frac{\phi}{f_a} \right) \right] \]

- **Mass:**
  \[ m_\phi = \frac{\Lambda^2}{f_a} \]

**Naturally light!**
(For large \( f_a \))
**Couplings fixed by \( f_a \)**

- **Photon coupling**
  \[
  \mathcal{L} \supset \frac{1}{4} g_{\phi \gamma \gamma} \phi F_{\mu \nu} \tilde{F}^{\mu \nu} \\
  g_{\phi \gamma \gamma} \sim \frac{\alpha}{4\pi f_a}
  \]

- **Gluon coupling**
  \[
  \mathcal{L} \supset \frac{1}{4} g_{\phi g g} \phi G_{\mu \nu} \tilde{G}^{\mu \nu} \\
  g_{\phi g g} \sim \frac{\alpha_s}{2\pi f_a}
  \]

At low energies

**electric dipole coupling**

\[
\mathcal{L} \supset -i g_d \phi \bar{N} \sigma_{\mu \nu} \gamma^5 N F^{\mu \nu} \\
g_d \sim 10^{-6} \text{GeV}^2 \left( \frac{10^{10} \text{GeV}}{f_a} \right)
\]
The ALP has no clue where to start

Field is stuck because of Hubble “breaking”
The ALP has no clue where to start

Can start moving...
ALP dark matter

Oscillations contain energy

behave like non-relativistic particles ($T=0$)
Why Cold? Inflation!

Field value

\[
\text{velocity} \sim \frac{p}{m} \sim \frac{\hbar}{m} \frac{d}{dx} \rightarrow 0
\]
Dark Matter Density

- Depends on the initial field value

\[ \rho_{\phi,0} \simeq 0.17 \frac{\text{keV}}{\text{cm}^3} \times \sqrt{\frac{m_0}{\text{eV}}} \sqrt{\frac{m_0}{m_1}} \left( \frac{\phi_1}{10^{11} \text{ GeV}} \right)^2 F(T_1) \]

- Pseudo-Goldstone

► Field value \( \phi_1 \leq \pi f_a \)

Naturally \( \phi_1 \sim \pi f_a \)
Axion(-like particle) Dark Matter

- Natural
- Possible
Axion Dark Matter
Detecting WISPy DM
Use a plentiful source of axions

- Photon Regeneration

ALP (dark matter)

Photon (amplified/detection)
Many efforts underway 😊

- ADMX
- MadMax
- CAPP-CULTASK
- + Many more: Abracadabra, Alps, Ariadne, Casper, EDM ring, FUNK, Haystac, HeXeniA, Iaxo, Organ, Rades, Sensei, Quax....
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A Bright Future
A little surprising stability
Axion Dark Matter

\[ \Gamma_{\text{pert}} = \frac{g_{\phi}{\gamma}^2 m_{\phi}^3}{64\pi} \]
Axion Dark Matter

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However: ALP field is extremely coherent → Bose enhancement possible
Axion Dark Matter

Without expansion/structure this would set a limit
(basically one ALP has to decay in the Universe for Bose enhancement to start)
Axion Dark Matter

Including expansion
(a second ALP has to decay before the photons from the first have red-shifted sufficiently)

Standard Stability bound

$$\Gamma_{\text{pert}} = \frac{g^2 \phi \gamma \gamma m^3}{64 \pi}$$
Axion Dark Matter

Photonics have mass in Plasma $\Rightarrow$ Prevents decay if $m_\phi \lesssim 2m_\gamma$
Exploring Beyond the Standard Scenario
Going Monodromic
Monodromy potential

\[ V(\phi) = \Lambda^4 \cos \left( \frac{\phi}{f} + \gamma \right) \]

Monodromy add-on

“Axion” potential (pseudo-Goldstone pot.)
Monodromy potential

\[ V(\phi) = \frac{1}{2}m^2 \phi^2 + \Lambda^4 \cos \left( \frac{\phi}{f} + \gamma \right) \]

Funny potential

+ enlarged field range
Advantages

- Allows to start with higher energy density
  ➔ More DM

Models in this region!
Interesting Phenomena??

Regions with “negative mass”

Instability + Parametric Resonance

→ Particle Production with $p \neq 0$?!?
Large $O(1)$ fluctuations

Fluctuations on small scales ➔ no problem with isocurvature ➔ Too small to collapse into miniclusters

\[ R_{\text{today}} \sim (10^5 - 10^6) \text{km} \sqrt{\frac{eV}{m_a}} \frac{a_{\text{structure}}}{a_{\text{today}}}, \]
Large $O(1)$ fluctuations

Fluctuations on small scales ➔ no problem with isocurvature) ➔ Too small to collapse into miniclusters

- Can we see such structures?
- Account for it in direct detection strategy

$\phi_1/f = 1000$
$\phi_1/f = 100$
$\phi_1/f = 45$

$R_{\text{today}}^{\text{in structure}} \sim (10^5 - 10^6) \text{km} \sqrt{\frac{\text{eV}}{m_a}} \frac{a_{\text{structure}}}{a_{\text{today}}}$,
Charging it
No conserved charge

⇒ absorption possible

Photon „absorbed in detector“

ALP (dark matter)
With conserved charge

\text{ALP} (dark matter)

\text{Photon absorbed in detector}
With conserved charge

Need particle and antiparticle to combine → suppressed

Higher order interaction → suppressed

→ Need new methods for detection!
Assymmetric Charge

• DM could (mostly) consist of only one type of charge
• Natural mechanism Affleck-Dine

→ No antiparticles

→ Need new methods for detection!
Assymmetric Charge

- DM could (mostly) consist of only one type of charge
- Natural mechanism Affleck-Dine

⇒ No antiparticles

⇒ Need new methods for detection!
⇒ Possibility for new large structures: Q-Balls
Conclusions
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• Dark Matter may be ALPy 😊
  ➡ New Search opportunities!
  ➡ Searches ongoing!

➡ Unusual places may be viable
➡ Crazy things to explore!
➡ Novel Detection techniques required
Conclusions

• Dark Matter may be Axiony/WISPy 😊
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Columbus' Theory: Tenerife – Jakarta ~ 3000 miles
Actual distance: ~ 7300 miles

Lesson:
Theory doesn't have to be correct in order to find something ;-)!
➔ Go Explore + Be prepared for surprises