

Title: Dark Sector Theory

Speakers:

Collection: TRISEP 2023

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URL: <https://pirsa.org/23060073>

Axion (Wave) DM

Dark Matter

L1: DM exists $\ddagger \frac{\Omega_{\text{CDM}}}{\Omega_m} = 0.84$ ^{CMB}

L2: Large landscape for $\rho_{\text{de}} \text{ DM (in mix)}$,
but not everything goes

"L3": WIMPs are more interesting than you think!

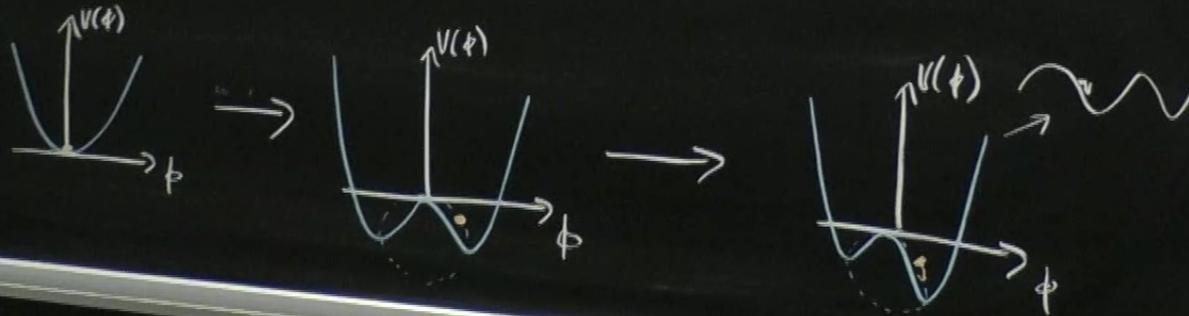
L / . WIMPs are more interesting than you think!

Axion (Wave) DM

Last time: started cosmology*

Today: finish, QCD axion briefly,
how to detect?

* Three stages:



Details: in an FRW Universe

$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0$$

For here: scale factor R

axion: a

$$H \gg m_a \Rightarrow \ddot{a} + 3H\dot{a} \approx 0 \Rightarrow a = a_0 = \text{const}$$

$$H \ll m_a \Rightarrow \ddot{a} + m_a^2 a \approx 0 \Rightarrow a(t) = a_0 \cos(m_a t + \varphi)$$

$$H \gg m_a \Rightarrow \ddot{a} + 3H\dot{a} \approx 0 \Rightarrow a = a_0 = \theta_0 f a$$

$$H \ll m_a \Rightarrow \ddot{a} + m_a^2 a \approx 0 \Rightarrow a(t) = a_0 (\cos(m_a t + \varphi))$$

Use WKB, ansatz $a(t) = A(t) \cos(m_a t + \varphi)$

Ex: slowly varying $A(t)$, $A \propto R^{-3/2}$

Recall: $\rho \propto a^{-3} \propto R^{-3} \Rightarrow$ exactly what CDM does

QCD Axion "Briefly" \rightarrow "QCD Axion Precisely" (orton +

Strong CP problem

$$\mathcal{L}_{\text{QCD}} \supset -\theta \frac{\alpha_s}{8\pi} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

$$\Rightarrow \text{neutron EDM } \times \Rightarrow \theta < 10^{-10}$$

Why?

$$\mathcal{L}_a = \frac{1}{2} (\partial a)^2 + \frac{a}{f_a} \frac{\alpha_s}{8\pi} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

non mass decay

$$V(a) = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4m_u m_d}{(m_u + m_d)^2} \sin^2 \left(\frac{a}{2f_a} - \frac{\theta}{2} \right)}$$

CAUTION

DO NOT TOUCH THE BOARD
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high mass, heavy

$$V(a) = m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{a}{2f_a} - \frac{\theta}{2}\right)}$$

$$\mathcal{L}_a \supset -\frac{1}{2} \underbrace{\left(\frac{m_u m_d}{(m_u + m_d)^2} \cdot \frac{m_\pi^2 f_\pi^2}{f_a^2} \right)}_{m_a^2} a^2$$

$$m_a f_a \approx m_\pi f_\pi \Rightarrow f_a < M_{pl} \Rightarrow m_a > 10^{-12} \text{ eV}$$

CAUTION

DO NOT TOUCH THE BOARD WHEN
IT IS BEING USED BY OTHERS.
IF A SIGNATURE IS GIVEN
THE BOARD IS NOT TO BE
USED FOR OTHER PURPOSES.

Axion Detection

$$\mathcal{L} \supset -\frac{1}{4} \underbrace{g_{\alpha\beta\gamma\delta}}_{\text{dim} = -1} \underbrace{F^{\mu\nu} \tilde{F}_{\mu\nu}}_{\text{dim} = 5} = g_{\alpha\beta\gamma\delta} a \vec{E} \cdot \vec{B}$$

$$g = \mathcal{O}(1) \times \frac{\alpha}{2\pi f_a} \approx \frac{\alpha m_a}{2\pi m_{\pi} f_{\pi}}$$

CAUTION

BE CAREFUL NOT TO TOUCH THE BOARD WHEN IT IS HOT

IT IS DANGEROUS TO TOUCH THE BOARD WHEN IT IS HOT

PLEASE PROTECT YOURSELF

Why \vec{B} ?

$$B: 10 \text{ T} \approx 1.95 \times 10^3 \text{ eV}^2$$

$$E: 10 \text{ kV/cm} \approx 0.65 \text{ eV}^2$$

Why B?

$$B: 10 \text{ T} \approx 1.95 \times 10^3 \text{ eV}^2$$

$$E: 10 \text{ kV/cm} \approx 0.65 \text{ eV}^2$$

Axion Decay $a \rightarrow \gamma \gamma$

$$\Gamma \propto g^2 m_a^3$$

\Rightarrow check, but for $m_a \ll 100 \text{ eV}$, safe

Axion-Photon Mixing

$$\Gamma(a \rightarrow \gamma) \sim g^2 B L$$

$$\text{CAST: } g < 6.6 \times 10^{-11} \text{ GeV}^{-1}$$

Axion Electrodynamics

$$d: (\square + m_a^2)a = g \vec{E} \cdot \vec{B} \stackrel{!}{=} 0$$

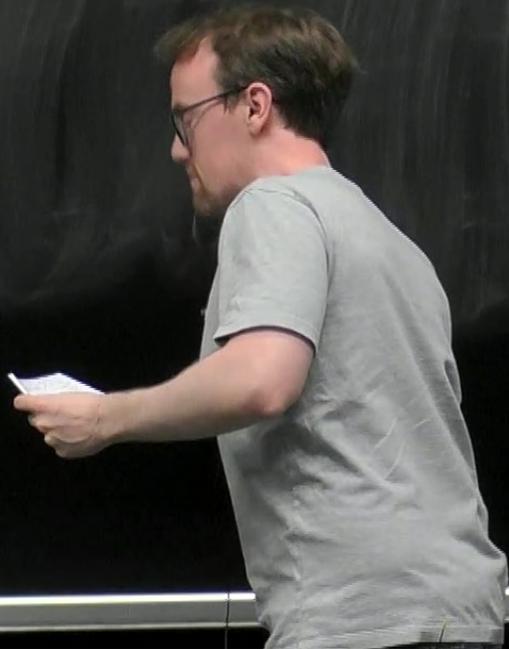
$$A^\mu: \partial_\nu F^{\mu\nu} = -J^\mu + \partial_\nu (g a \tilde{F}^{\nu\mu}) + g(\partial a) \tilde{F}^{\nu\mu}$$

totally skew

$$\text{Bianchi identity: } \partial_{[\mu} F_{\nu\sigma]} = 0 \quad \textcircled{1}$$

$$\Rightarrow \partial_{[\mu} \tilde{F}^{\mu\nu]} = 0$$

$$F^{0i} = -E^i, \quad F^{ij} = -\epsilon^{ijk} B^k$$
$$\tilde{F}^{0i} = -B^i, \quad \tilde{F}^{ij} = \epsilon^{ijk} E^k$$



CAUTION
TO AVOID AN ACCIDENT AND PREVENT DAMAGE
PLEASE BE CAREFUL IN THE WORKING AREA
IF IN DANGER OF AN ACCIDENT
PLEASE STOP WORK IMMEDIATELY
PLEASE WEAR YOUR SAFETY GEAR

$$\vec{\nabla} \cdot \vec{B} = 0$$

$$\vec{\nabla} \times \vec{E} = -\partial_t \vec{B}$$

$$\vec{\nabla} \times \vec{B} = \partial_t \vec{E} + \vec{J} + g(\vec{B} \partial_t a - \vec{E} \times \vec{\nabla} a)$$

$$\vec{\nabla} a \sim m a \vec{v} \quad a \ll \partial_t a$$

$$\partial_t a \sim m a a$$

CAUTION

BE CAREFUL FOR LENSES AND MIRRORS WHICH
MAY BE HOT OR VERY BRIGHT AT THE SOURCE

IT IS ESSENTIAL TO WEAR
APPROPRIATE PROTECTIVE GEAR

PLEASE CONTACT US IF
NECESSARY

$$\vec{\nabla} \cdot \vec{B} = 0$$

$$\vec{\nabla} \times \vec{E} = -\partial_t \vec{B}$$

$$\vec{\nabla} \times \vec{B} = \partial_t \vec{E} + \vec{J} + \frac{1}{c} (\vec{B} \partial_t a - \vec{E} \times \vec{\nabla} a)$$

$$\vec{\nabla} a \sim m a \vec{v} \quad a \ll \partial_t a$$

$$\partial_t a \sim m a$$

Ex: Repeat
for $\mathcal{L} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu}$

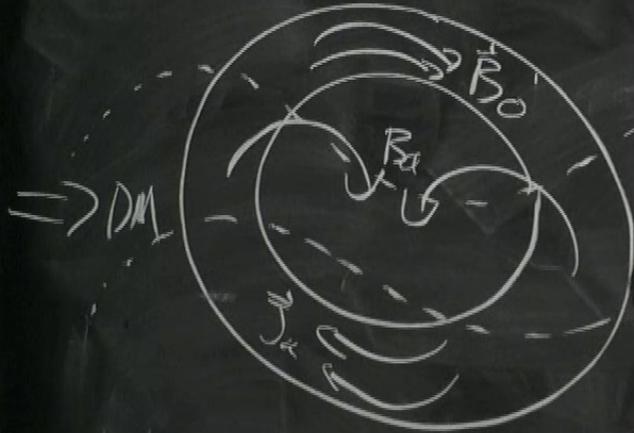
CAUTION

DO NOT TOUCH THE BOARD WHEN
PRESENTED BY THE STAFF OF THE DEPT.

IT IS PROHIBITED TO SMILE
AND LAUGH WHILE PRESENTING.

BY THE DEPT. STAFF

Ex (ABRA, DM Radio)



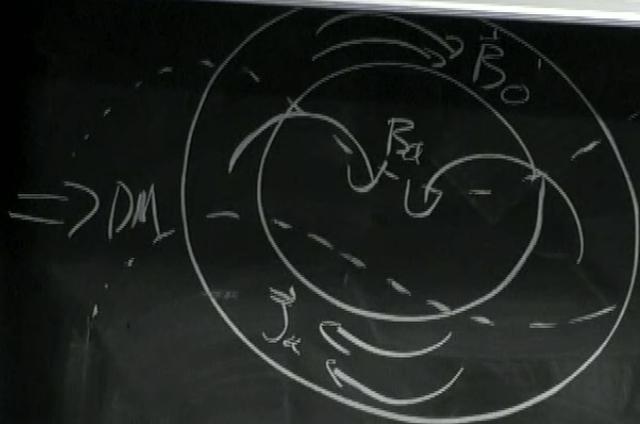
$$\vec{B}_a \sim g \vec{B}_0 (\partial a) L$$

$$g = \text{CAST}$$

$$L = 1\text{m}$$

$$\partial a \sim m_a \frac{\sqrt{2\rho_\chi}}{2m_a}$$

$$\approx 2 \times 10^{-3} \text{eV}^2$$



$$g = \text{CAST} \quad \partial u \sim \frac{\sqrt{2\rho}}{2m\alpha}$$

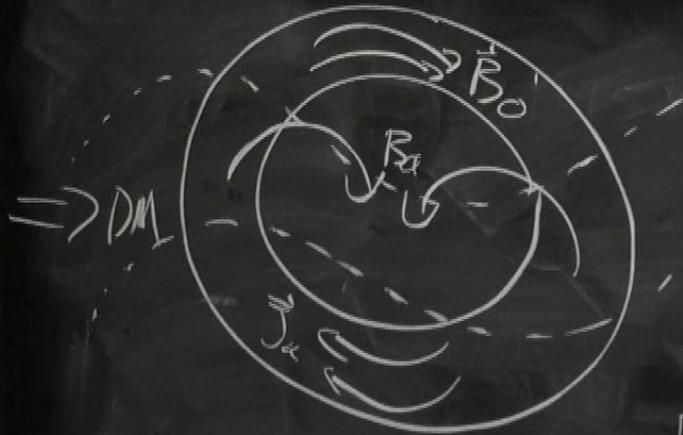
$$L = 1m \approx 5 \times 10^6 \text{ eV}^{-1} \approx 2 \times 10^{-3} \text{ eV}^2$$

$$B_a \sim (6.6 \times 10^{-20} \text{ eV}^{-1}) \times (2 \times 10^{-3} \text{ eV}^2)$$

$$\cdot (5 \times 10^6 \text{ eV}^{-1}) \times 10 \text{ T}$$

$$\sim 6.6 \times 10^{-15} \text{ T} \sim 6.6 \text{ fT} \ll B_2$$

Ex (ABRA, DM Radio)



$$\vec{B}_a \sim g \vec{B}_0 (2\pi a) L \oplus$$

$$g = \text{CAST} \quad \partial u \sim \frac{\sqrt{2\rho_x}}{2\pi a}$$

$$L = 1 \text{ m} \sim 5 \times 10^6 \text{ eV}^{-1} \quad \sim 2 \times 10^{-3} \text{ eV}^2$$

$$B_a \sim (6.6 \times 10^{-20} \text{ eV}^{-1}) \times (2 \times 10^{-3} \text{ eV}^2)$$

$$\cdot (5 \times 10^6 \text{ eV}^{-1}) \times 10 \text{ T}$$

$$\sim 6.6 \times 10^{-15} \text{ T} \sim 6.6 \text{ fT} \ll B_0$$

Exc: check \oplus transforms consistently under parity

How would this go for a scalar?