The Cosmological Tension of Ultralight Axion Dark Matter and its Solutions

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Jeff Dror, JML

Ultralight Axion Dark Matter

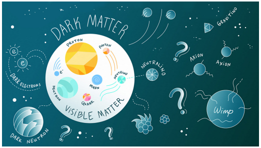

Photo Credit: Symmetry Magazine

- Ultralight Dark Matter : $m \sim 10^{-22} - 10^{-13}$ eV
- "Fuzzy" Regime: $m \sim 10^{-22} - 10^{-21}$ eV

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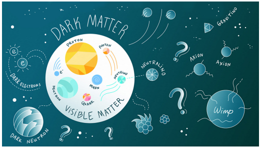

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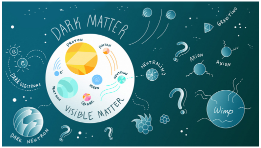
  Continuous Shift Symmetry $\implies$ Small mass natural



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  Broken to discrete shift symmetry:

$$V(a) = \mu^4 \cos\left(\frac{a}{f_a}\right) \implies m_a \simeq \frac{\mu^2}{f_a}$$

- Today: Derive bounds on ULA DM from the matter-power spectrum & describe model building techniques to (partially) evade these bounds.

Couplings to Standard Model

- Anomalous & derivative couplings $\propto 1/f_a$
- Axion - Photon Coupling

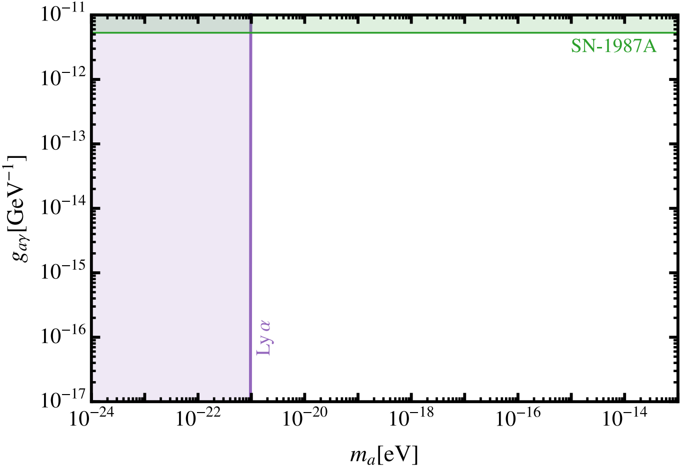
$$\mathcal{L} \supset \frac{C_{a\gamma}\alpha_{EM}}{8\pi f_a} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

- Axion - Nucleon Coupling

$$\mathcal{L} \supset \frac{C_{aN}}{f_a} \partial_\mu a \bar{N}\gamma^\mu\gamma_5 N$$

- Other Couplings
  - Electron: [1709.07852 - Graham et al]
  - Muon: [2005.11867 - Graham et al] & [2006.10069 - Janish et al]

Photon Coupling Parameter Space



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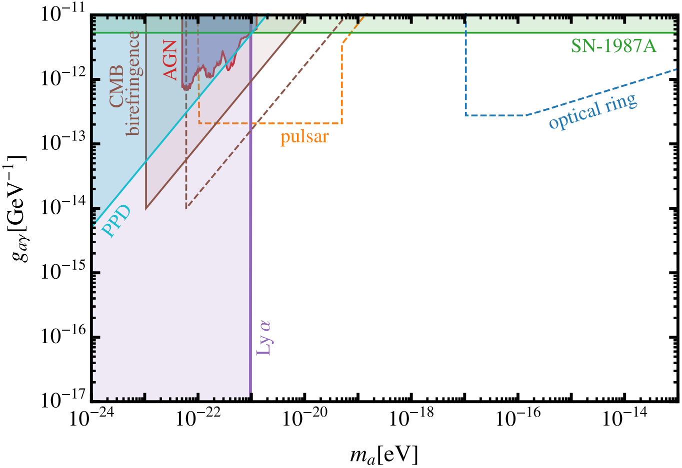

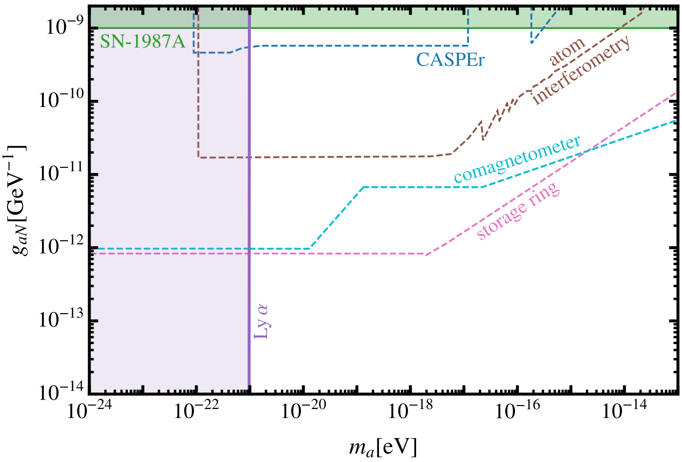

10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
$g_{aN}[\mathrm{GeV}^{-1}]$
SN-1987A
CASPEr
atom interferometry
comagnetometer
storage ring
Ly α
10^{-24}
10^{-22}
10^{-20}
10^{-18}
10^{-16}
10^{-14}
$m_a[\mathrm{eV}]$

Bounds from the Matter-Power Spectrum (Rough)

- $V = \mu^4 \cos \frac{a}{f_a}$

$$m_a^2 \sim \frac{\mu^2}{f_a} \qquad \lambda_a \sim \frac{\mu^4}{f_a^4}$$

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- Using

$$\left(\frac{\delta\rho}{\rho}\right)_{eq} \lesssim 10^{-3} \quad \& \quad \rho_{DM}^{eq} \sim \mathrm{eV}^4 \implies a_{eq} \sim \frac{\mathrm{eV}^2}{m_a}$$

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- We find

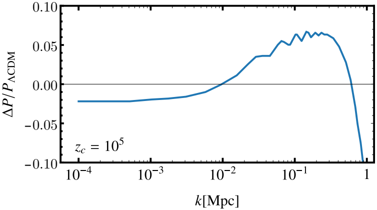
$$\left.\frac{\lambda_a a^4}{m_a^2 a^2}\right|_{eq} \lesssim 10^{-3} \Longrightarrow \frac{\text{eV}^4}{m_a^2 f_a^2} \lesssim 10^{-3}$$

The Rough Cosmological Bound

$$f_a \gtrsim 3 \times 10^{12}\ \text{GeV}\left(\frac{10^{-20}\ \text{eV}}{m_a}\right)$$

Bounds from the Matter-Power Spectrum (Numerical)

- Numerical studies of the Matter-Power Spectrum $\longrightarrow$
- Hubble friction freezes axion until $H(z_c) \simeq m_a$ and oscillations begin
- Ultralight axion acts similar to warm dark matter: require $z_c \gtrsim 10^5$



[1806.10608 - Poulin et al]

$$\rho_{DM} \simeq \frac{1}{2} m_a^2 a(z)^2$$

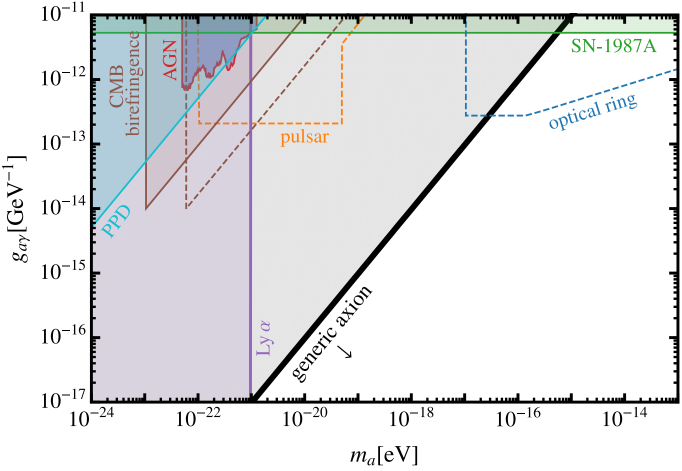
$$a(z) \propto (1+z)^{3/2}$$

The Numerical Cosmological Bound

$$f_a \gtrsim 1.2 \times 10^{13} \text{ GeV} \left(\frac{10^{-20} \text{ eV}}{m_a} \right)$$

Very close to rough bound

Photon Coupling Parameter Space



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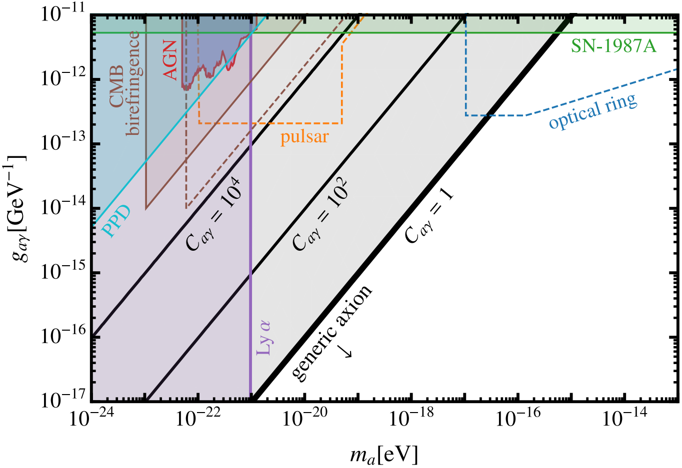

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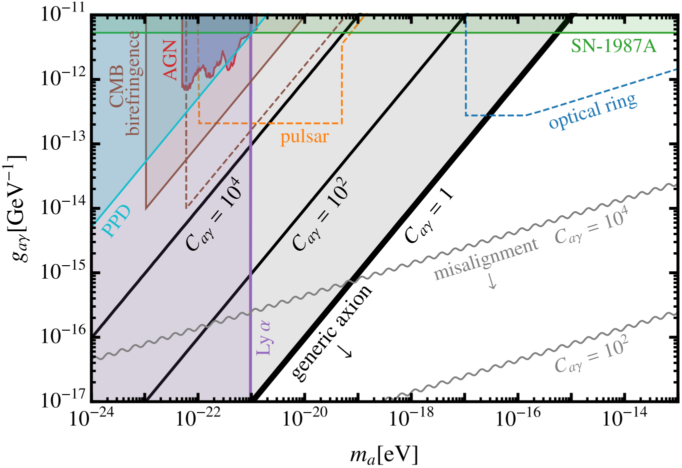
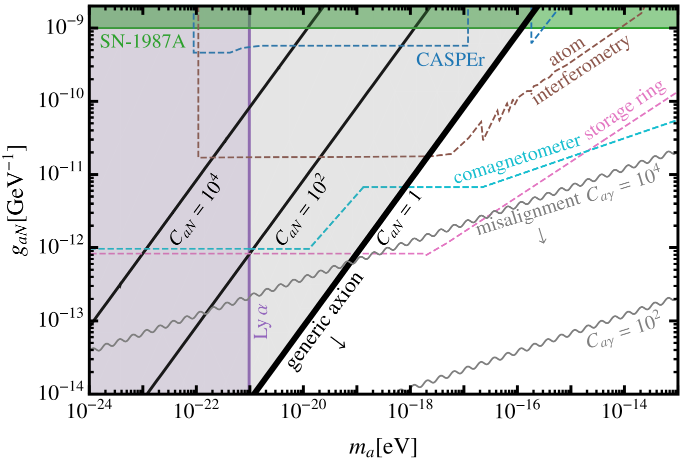
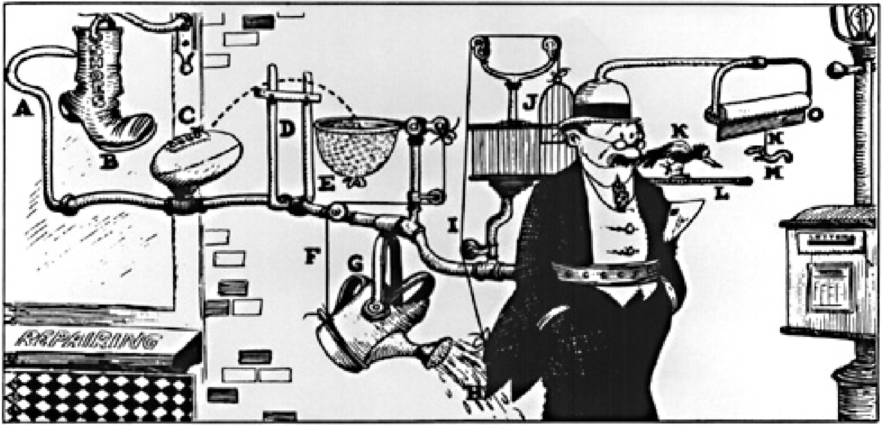


Nucleon Coupling Parameter Space



Q:What are experiments looking for?



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Escaping the Power Spectrum

- **Need to raise coupling to visible matter for a given mass $\Longrightarrow$ non-trivial model building**
- Focus on photon coupling:

$$\mathcal{L} \supset \mu^4 \cos\frac{a}{f_a} + \frac{C_{a\gamma}\alpha_{EM}}{8\pi f_a} aF\tilde{F}$$

Need strategies to increase the value of $C_{a\gamma}$

- Considered in the literature for QCD axions & axion inflation

[hep-ph/0409138 - Kim, Nilles Peloso]
[1503.01015 - Shiu, Staessens, Ye]
[1503.02965 - Shiu, Staessens, Ye]
[1511.00132 - Choi, Im]
[1511.01827 - Kaplan, Rattazzi]
[1611.09855 - Farina et al]
[1709.06085 - Agrawal et al]
[1806.09621 - Agrawal, Fan, Reece]
[1909.11685 - Choi, Shin, Yun]
[1910.11349 - Fraser, Reece]
...

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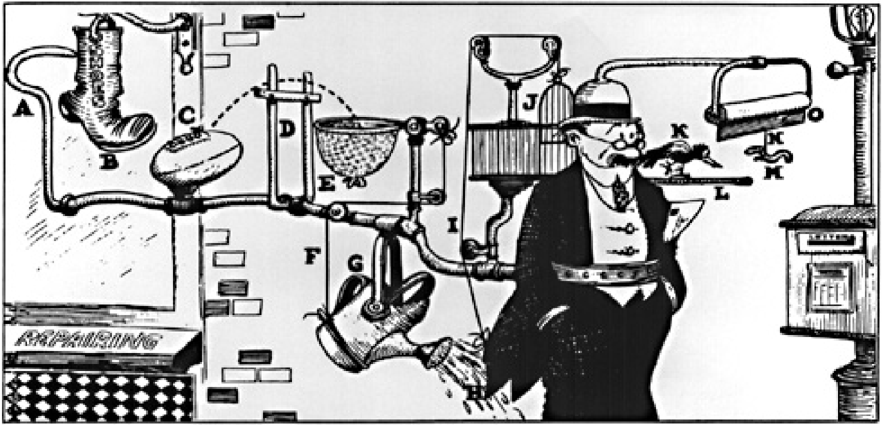

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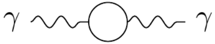
A: Rube Goldberg (Axion) Model: An axion that requires additional model building to be detectable

Escaping the Power Spectrum: Model Building

- **Large Charges**: simple idea - adjust fermion content

[1709.06085 - Agrawal, Fan, Reece,Wang]
[1806.09621 - Agrawal, Fan, Reece]

$$C_{a\gamma} = \mathrm{Tr}(Q_{EM}^2) \sim N_f Q_{EM}^2$$



$$\Longrightarrow \frac{N_f Q^2 e^2}{(4\pi)^2} \lesssim 1$$

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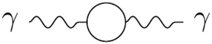

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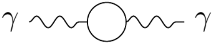

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- **Kinetic Mixing**: with two axions

$$\mathcal{L} \supset \frac{1}{2}(\partial a_1)^2 + \frac{1}{2}(\partial a_2)^2 + \epsilon \partial a_1 \partial a_2 + \mu^4 \cos \frac{a_1}{F_1} + \frac{\alpha}{8\pi F_2} a_2 F\tilde{F}$$

$$\Longrightarrow \mathcal{L} \supset \frac{\epsilon F_1}{F_2} \frac{\alpha}{8\pi F_1} a_1 F\tilde{F}$$

If $C_{a\gamma} = \epsilon F_1 / F_2 >> 1$, then axion-photon coupling is enhanced.

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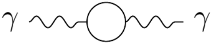

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This is not easily achieved in field theory

- **Discrete Symmetry**:
  1 axion and N non-abelian confining gauge sectors $G_{(n)}$

[1802.10093 - Hook]

$$\mathcal{L} \supset \frac{\alpha_s}{8\pi} \sum_{i=1}^{N} \left(\frac{a}{F_a} + \frac{2\pi i}{N} \right) G_{(i)} \tilde{G}_{(i)} + \frac{\alpha_{EM}}{8\pi F_a} a F \tilde{F}$$

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$$V(a) = \frac{C_2}{2}\frac{\mu^4}{F_a^2}a^2 - \frac{C_4}{4!}\frac{\mu^4}{F_a^4}a^4 + \cdots$$

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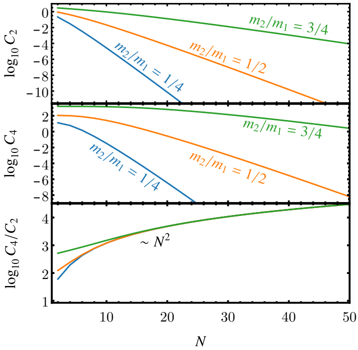
Large enhancement gives large deviations in matter-power spectrum

[1802.10093 - Hook]



Escaping the Power Spectrum: Model Building

- **Clockwork**: N axions a_i & N non-abelian confining gauge sectors $G_{(i)}$

$$\mathcal{L} \supset \sum_{i=1}^{N-1} \frac{\alpha_{i+1}}{8\pi} \left(\frac{\beta_i a_i}{F_i} + \frac{a_{i+1}}{F_{i+1}} \right) G_{(i+1)} \tilde{G}_{(i+1)} + \frac{\alpha_1}{8\pi F_1} a_1 G_1 \tilde{G}_1 + \frac{\alpha_{EM}}{8\pi F_N} a_N F \tilde{F}$$

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Integrating out heavy axions

$$\mathcal{L} \supset \mu_1^4 \cos\frac{a_N}{F_N \prod_i \beta_i} + \frac{\alpha_{EM}}{8\pi F_N} a_N F\tilde{F}$$

$$C_{a\gamma} = \prod_i \beta_i$$

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Even for modest β_i, large enough N gives significant enhancement

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- Can you model build the bound away? Sort of.
  - Large Charges/Lots of fermions - limited effectiveness
  - Kinetic mixing - doesn't seem to work from the EFT perspective. String constructions could work, but no concrete examples.
  - Using discrete symmetry - matter-power spectrum bound gets stronger, not viable.
  - Clockwork - viable. Unlimited effectiveness from EFT perspective, limited effectiveness in UV completions (?).