Ultralight Axion Dark Matter: Detectability, Constraints, and Model Building

Jacob M. Leedom
IPMU Seminar
October 7, 2020

arXiv:2008.02279, 20XX.XXXXX
Jeff Dror, JML

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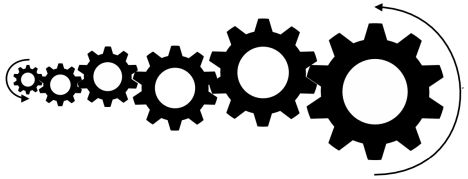
$|\mathrm{JML}\rangle = \frac{1}{\sqrt{2}}\left(\left|\right\rangle + \left|\right\rangle\right)$

(Also known as the Murayama State)

Outline

- **Ultralight Dark Matter & Axions**
  - Ultralight Dark Matter
  - Axions as Ultralight Dark Matter
  - Couplings to the Standard Model
- **Detecting Ultralight Axion Dark Matter**
  - Through Photon Coupling
  - Through Nucleon Coupling
  - Through Neutrino Coupling (?)
- **Bounds from the Matter-Power Spectrum**
  - Constraint on Generic Axions
  - Largely eliminates detectable axions at lower masses
- **Escaping the Power Spectrum**
  - Large charges
  - Kinetic mixing
  - Discrete symmetries
  - Clockwork



[1610.07962 - Giudice et al]

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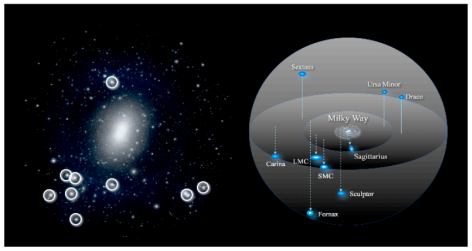
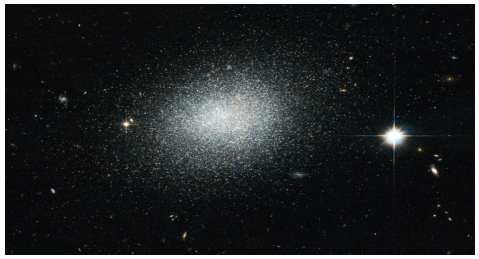


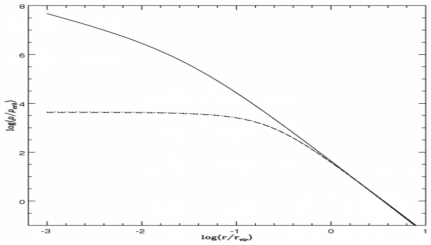
Missing Satellites

[UGC 5497 - Nasa]



Too Big to Fail

[0906.4447 - Popolo et al]



Cusp-Core

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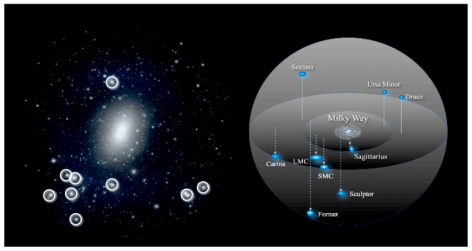

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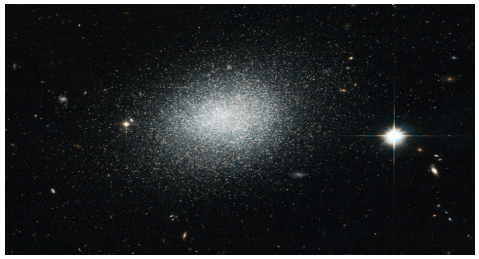

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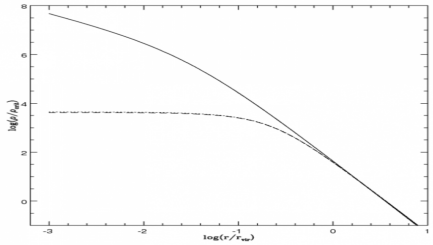

Cusp-Core

- Lyman-α Bound (& other purely gravitational considerations)

$$m \gtrsim \mathcal{O}(10^{-21}) \text{ eV}$$

Axions as Ultralight Dark Matter

- Historically: Strong CP Problem

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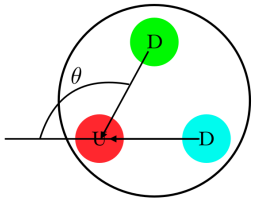

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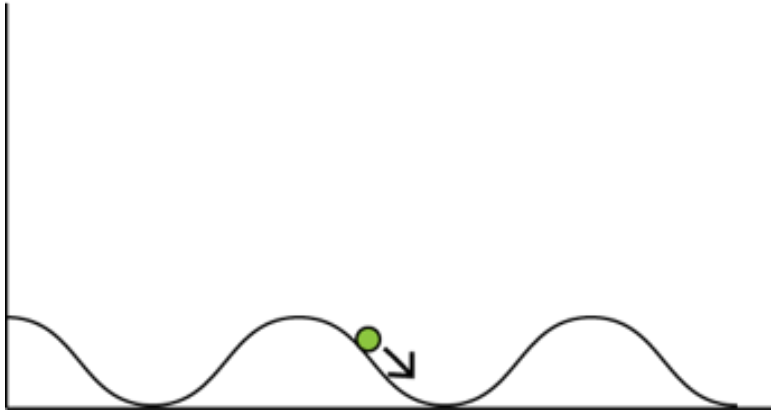
[1812.02669 - Hook]



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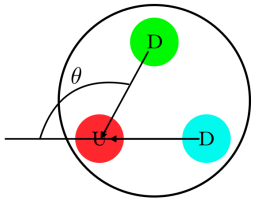

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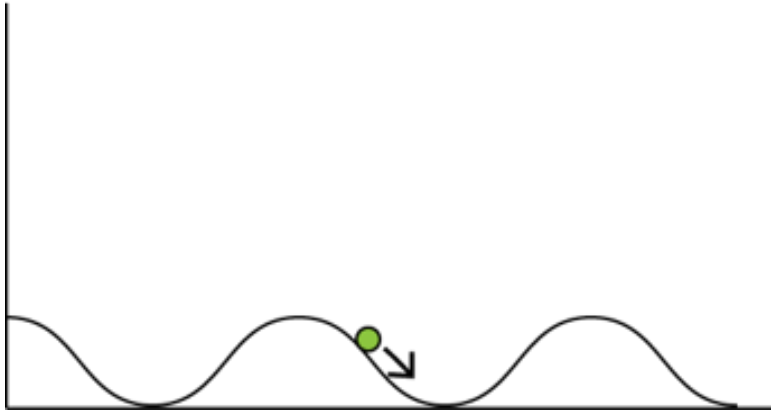

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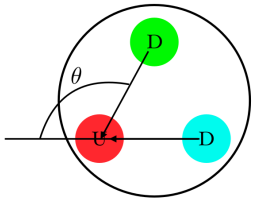

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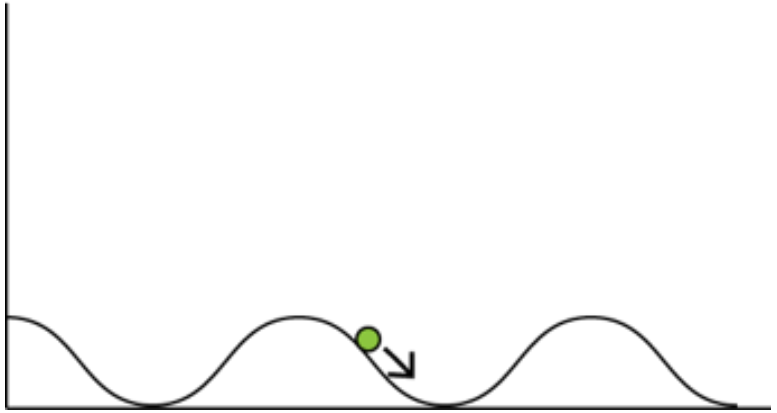

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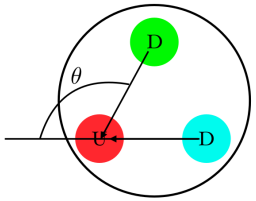

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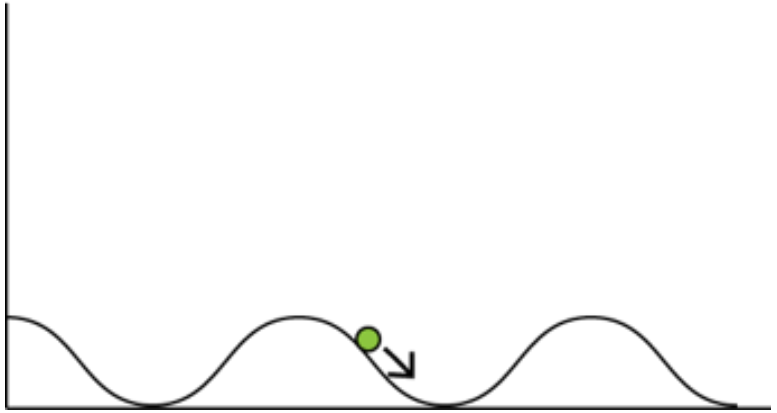

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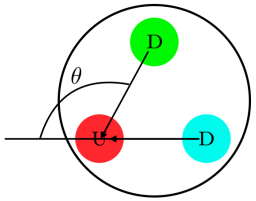

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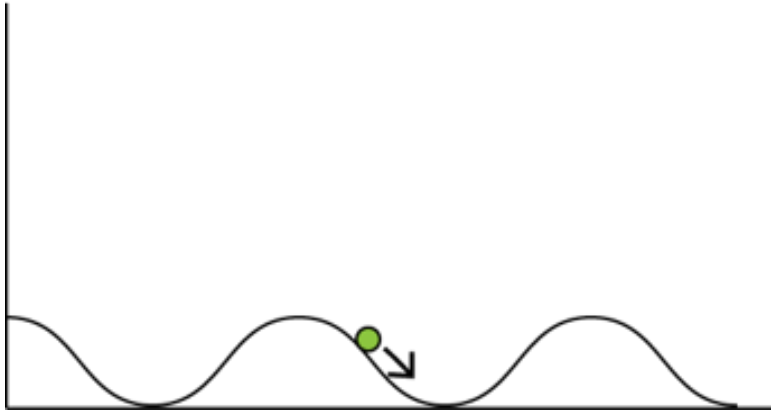

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- Can consider a as the goldstone boson of some global symmetry breaking or mode of higher form field

Couplings to Standard Model

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

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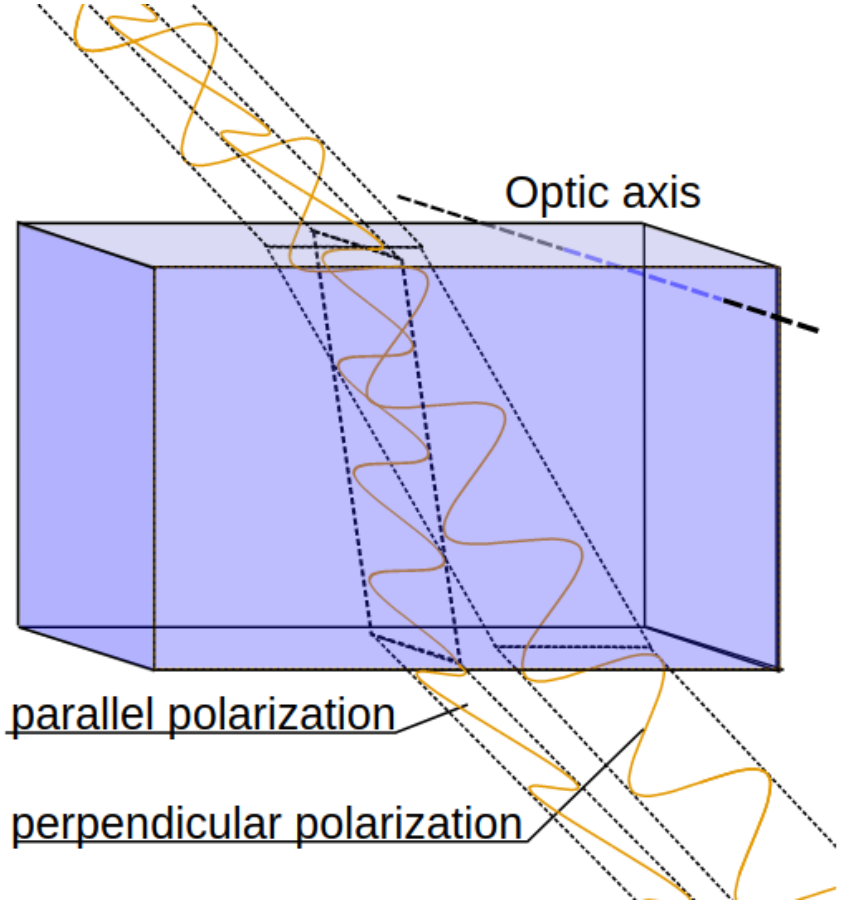
- Other Couplings
  - Gluon: [1708.08464 - Hook et al]
  - Electron: [1709.07852 - Graham et al]
  - Muon: [2005.11867 - Graham et al] & [2006.10069 - Janish et al]

Detecting Ultralight Axion Dark Matter: Photon Coupling

Axion birefringence → rotation of light polarization



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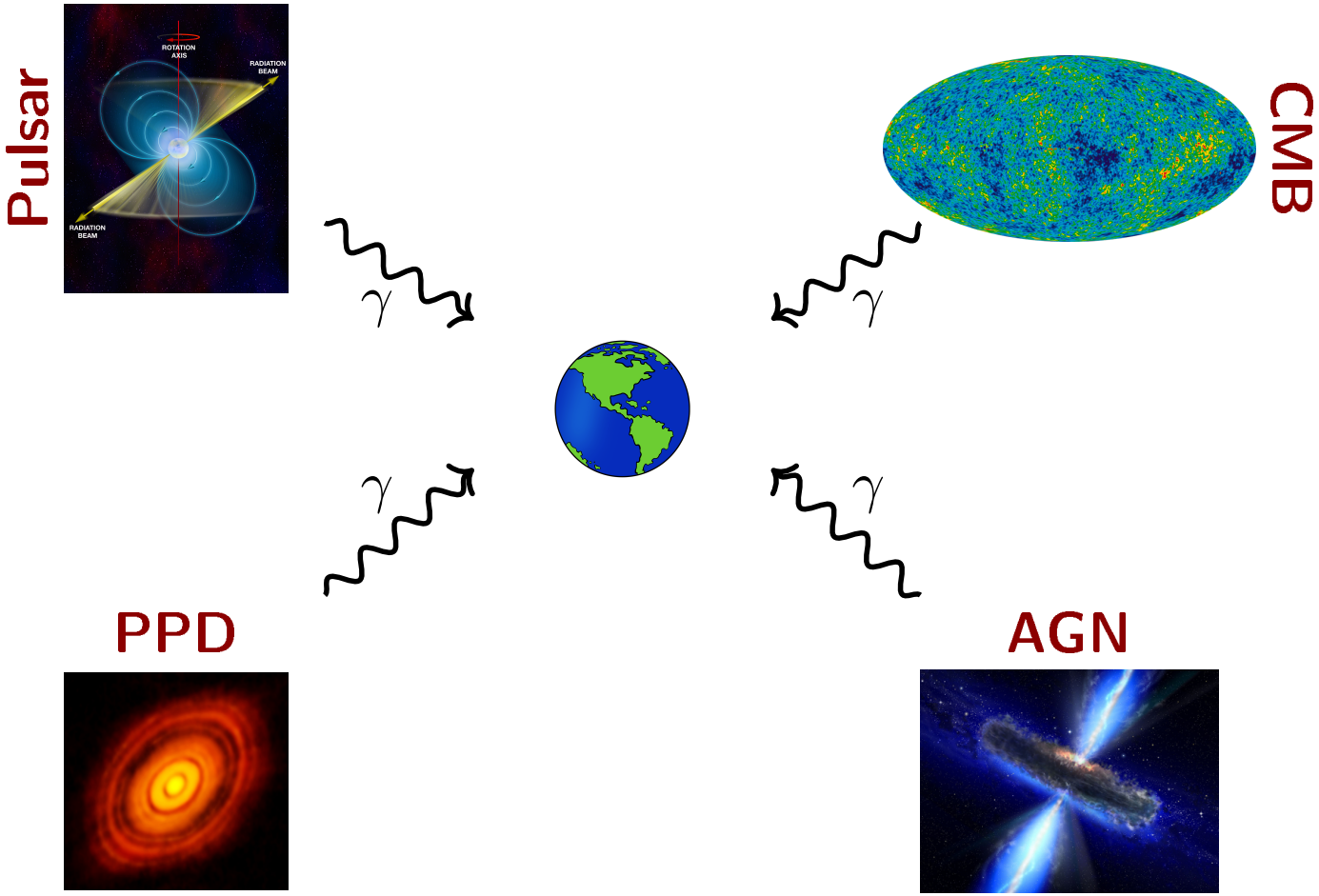
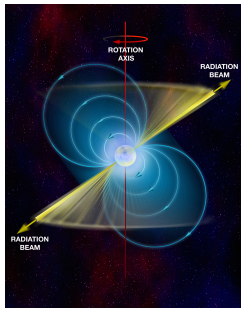


Detecting Ultralight Axion Dark Matter: Photon Coupling

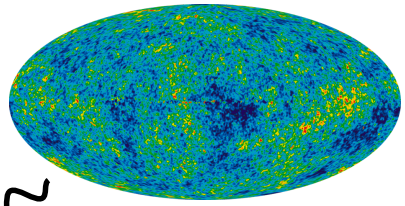
[Image credit - NRAO/AUI/NSF]
[Ivanov et al - 1811.10997]

Pulsar



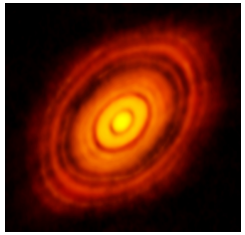
[Harari, Sikivie - 1992]
...
[Fedderke, Graham, Rajendran - 1903.02666]

CMB



[Image credit - WMAP]

PPD

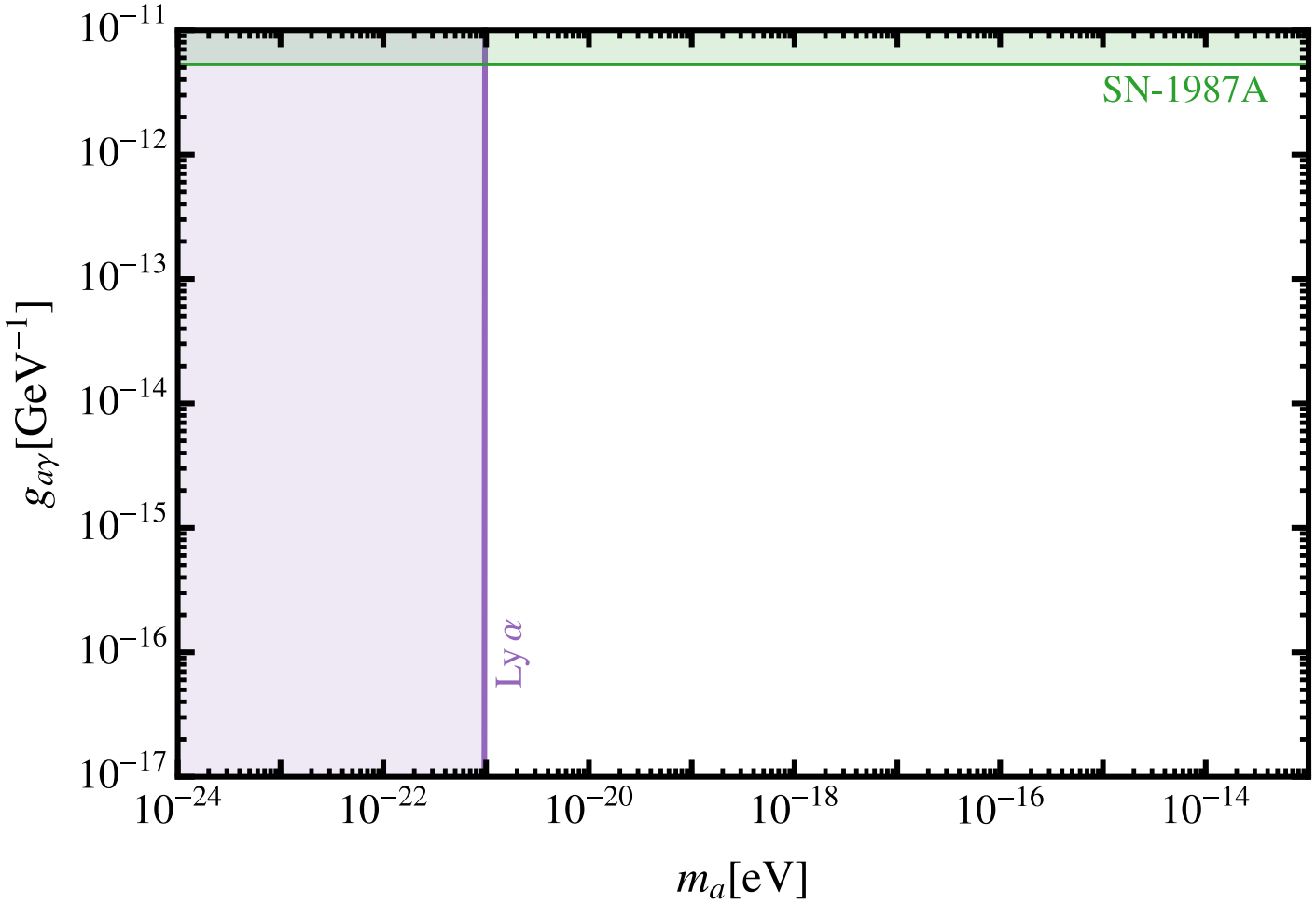


[Fujita, Tazaki, Toma - 1811.03525]
[Image credit - Wiki]

AGN

[Liu, Smoot, Zhao - 1901.10981]
[Image credit - ESA/NASA]

Photon Coupling Parameter Space



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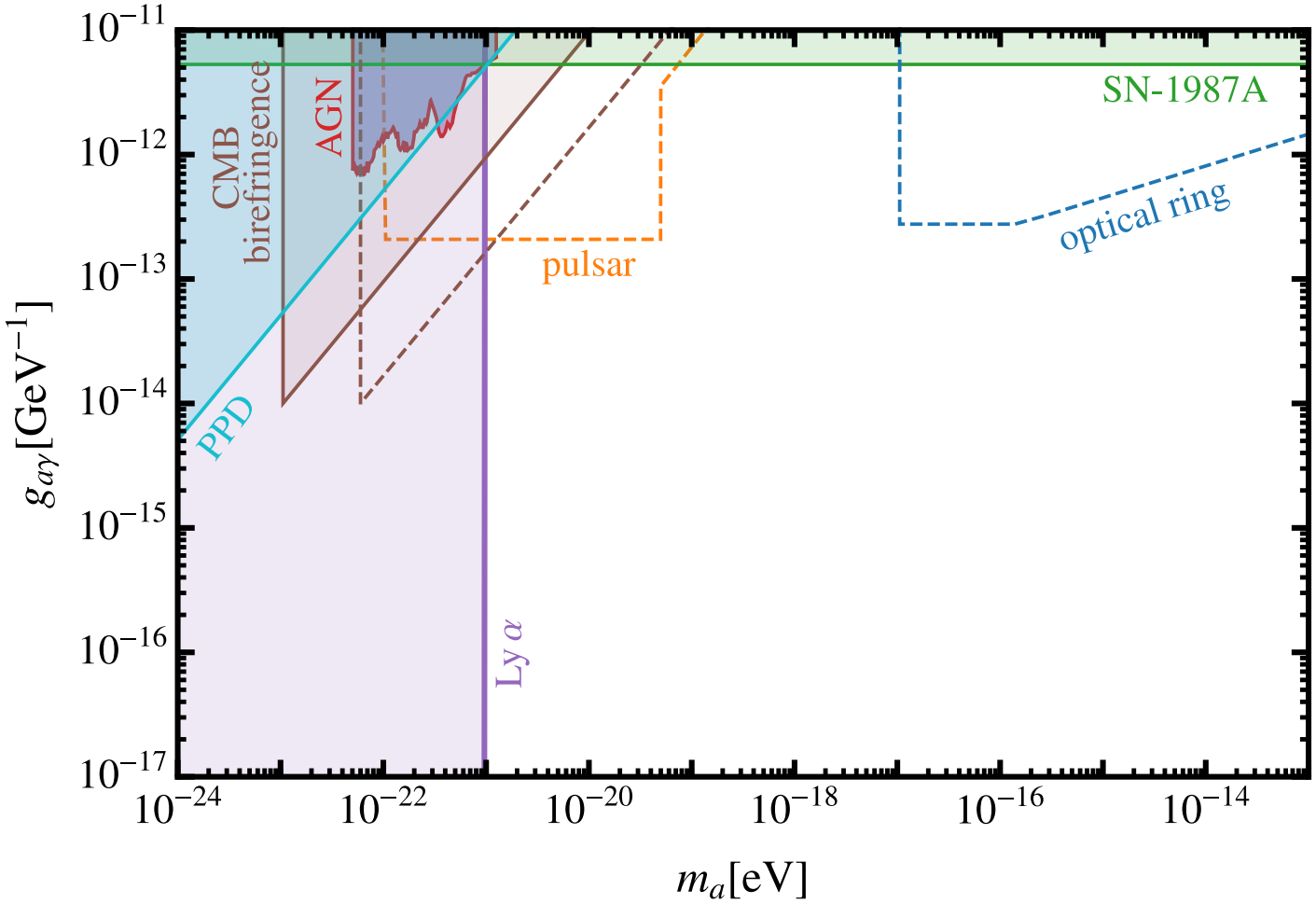
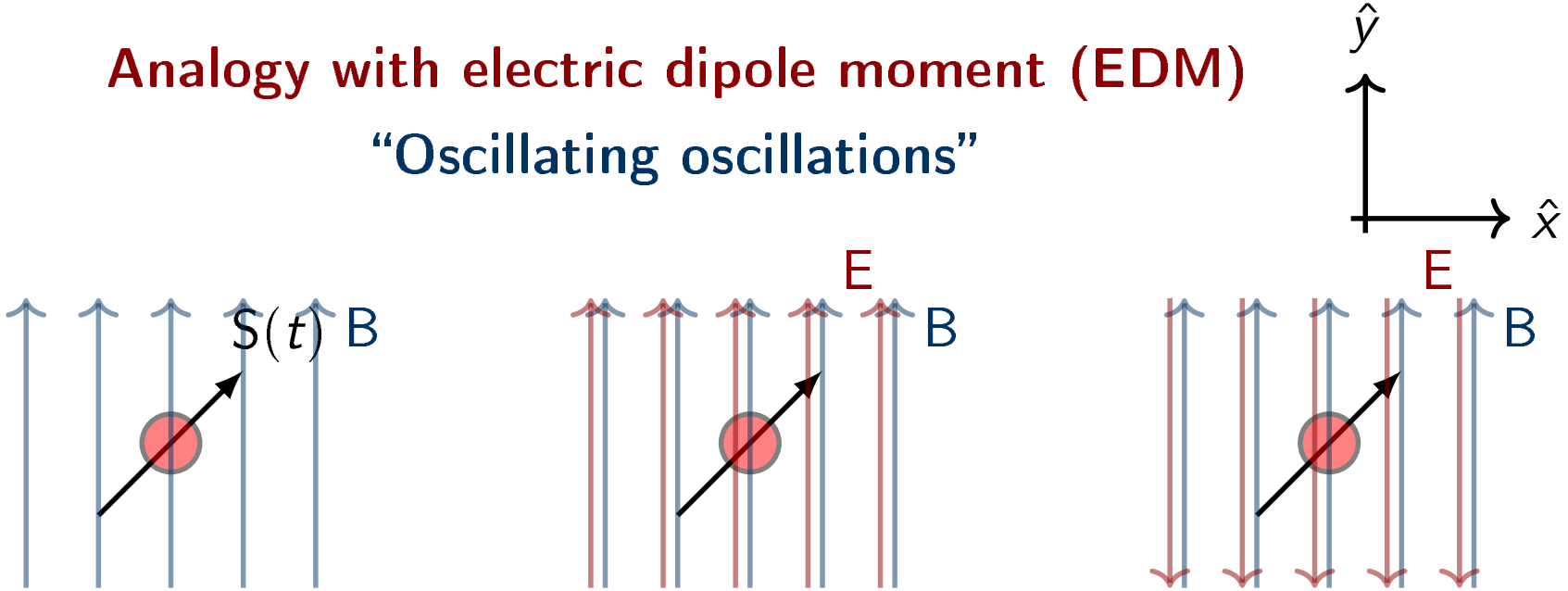


Analogy with electric dipole moment (EDM)

"Oscillating oscillations"



$$S_0\big[\cos(2\pi\mu Bt)\hat{x} + \sin(2\pi\mu Bt)\hat{y}\big]$$

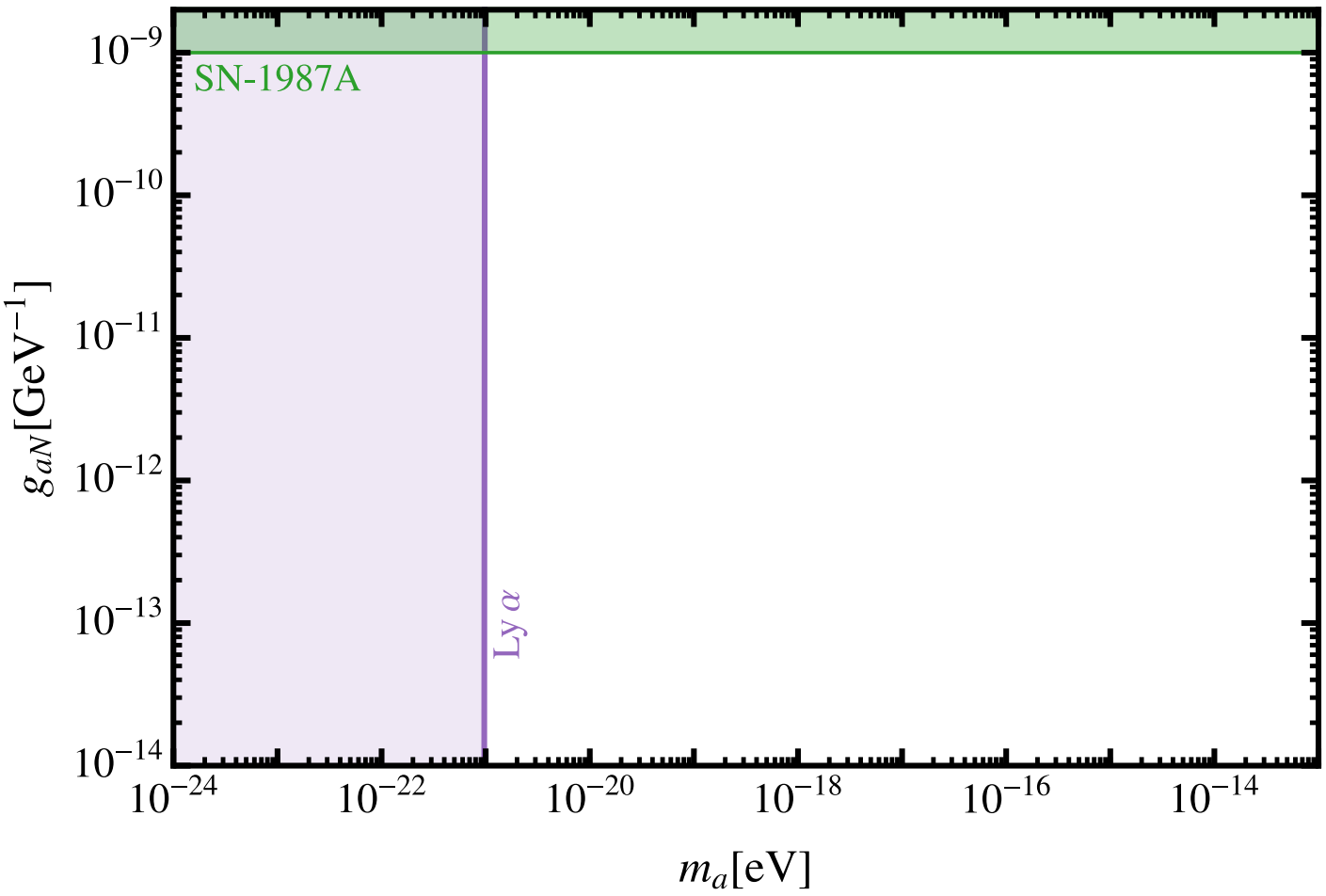
$$S_0\big[\cos(2\pi(\mu B + d_n E)t)\hat{x} + \sin(2\pi(\mu B + d_n E)t)\hat{y}\big]$$

$$S_0\big[\cos(2\pi(\mu B - d_n E)t)\hat{x} + \sin(2\pi(\mu B - d_n E)t)\hat{y}\big]$$

$$\mathcal{L} \supset g_{aN}\partial_\mu a\bar{N}\gamma^\mu\gamma_5 N \Longrightarrow H \supset \sqrt{2\rho_{DM}}\vec{v}\cdot\vec{\sigma}_N\cos(m_a t)$$

Axion acts like a magnetic field

Nucleon Coupling Parameter Space



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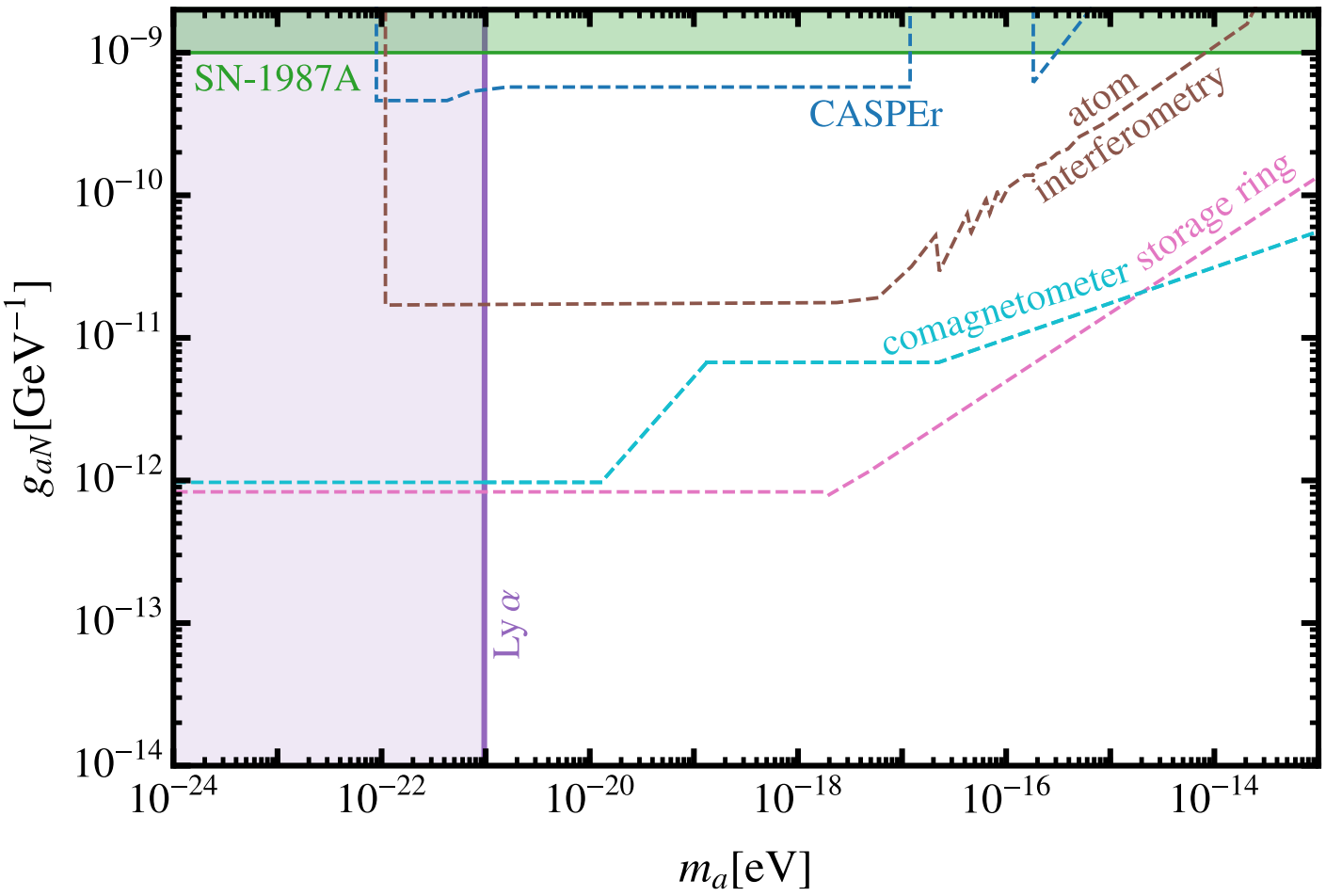
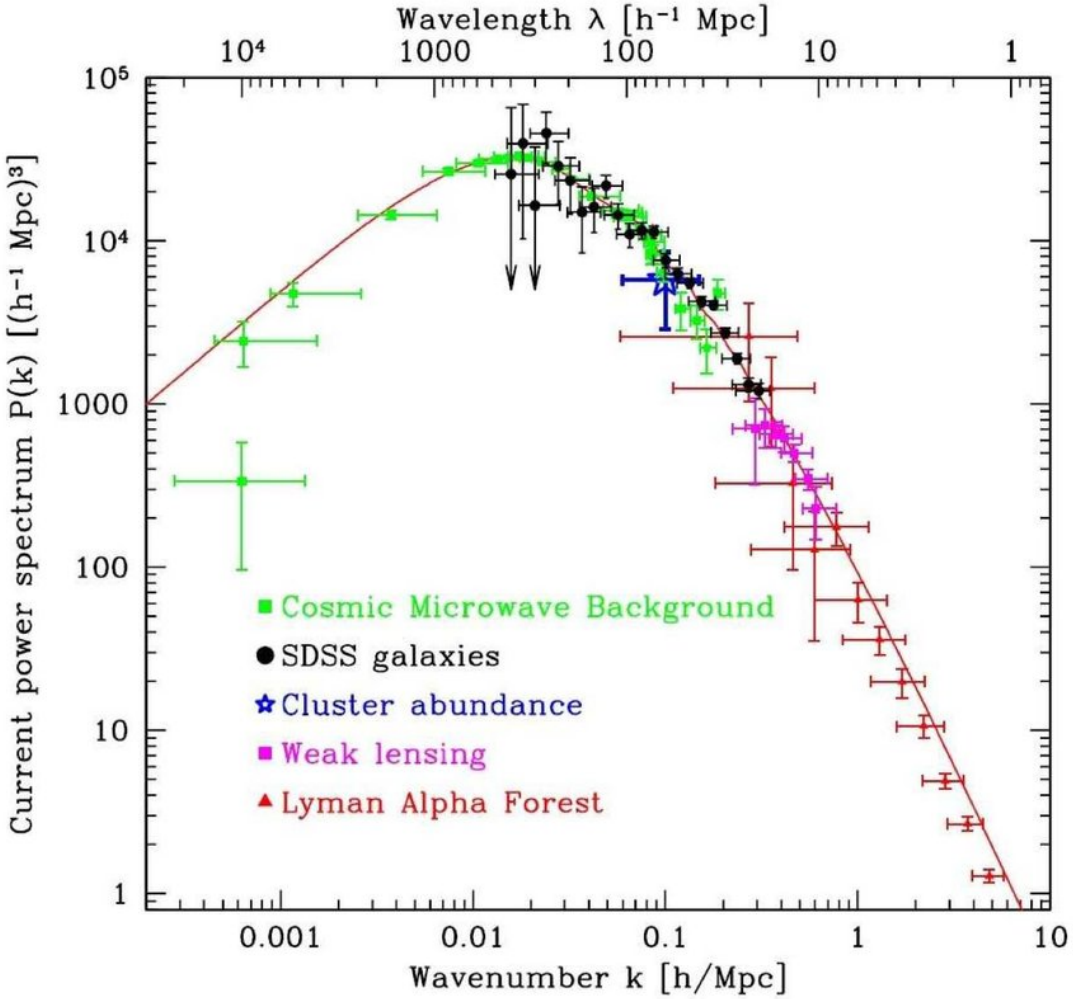


Bounds from the Matter-Power Spectrum (Rough)



[astro-ph/0207047v3 - Tegmark, Zaldarriaga]

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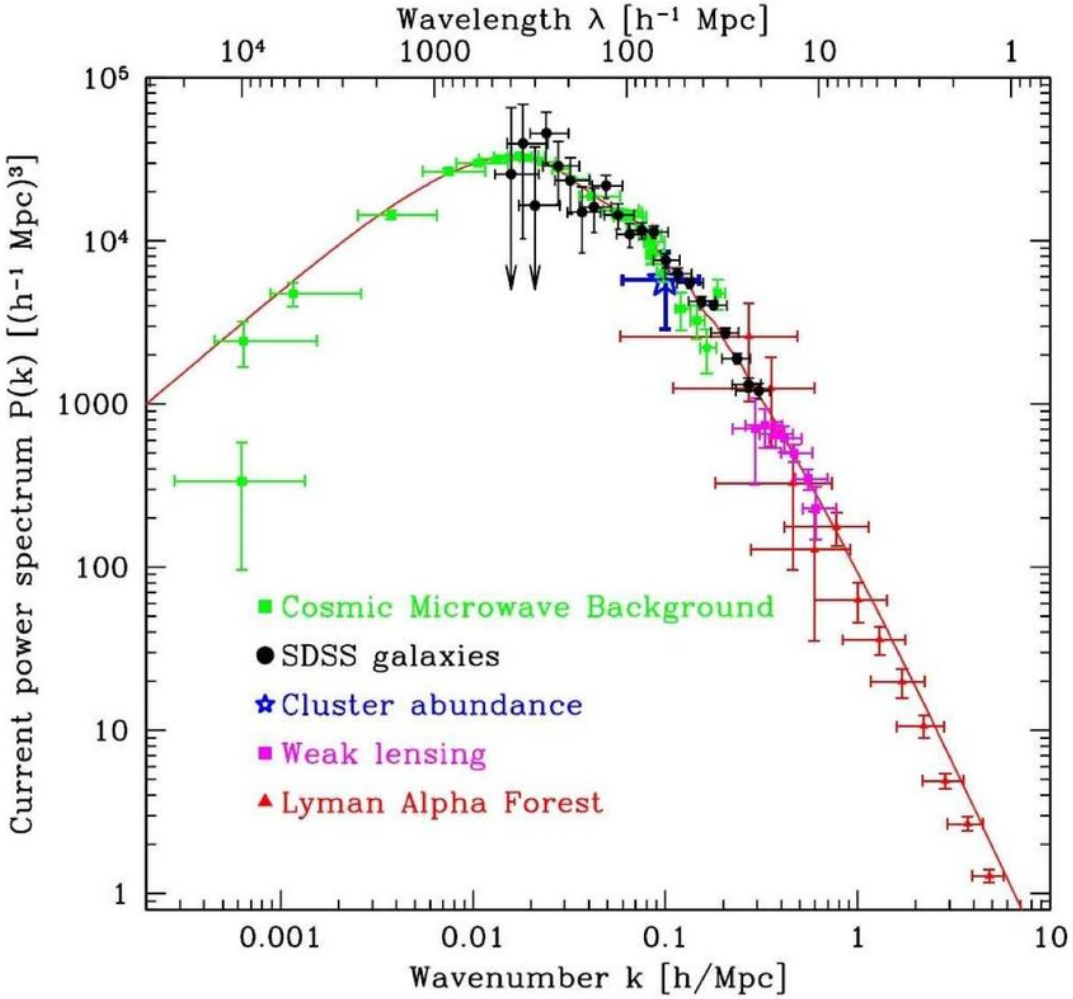

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$$V \sim \phi^n$$

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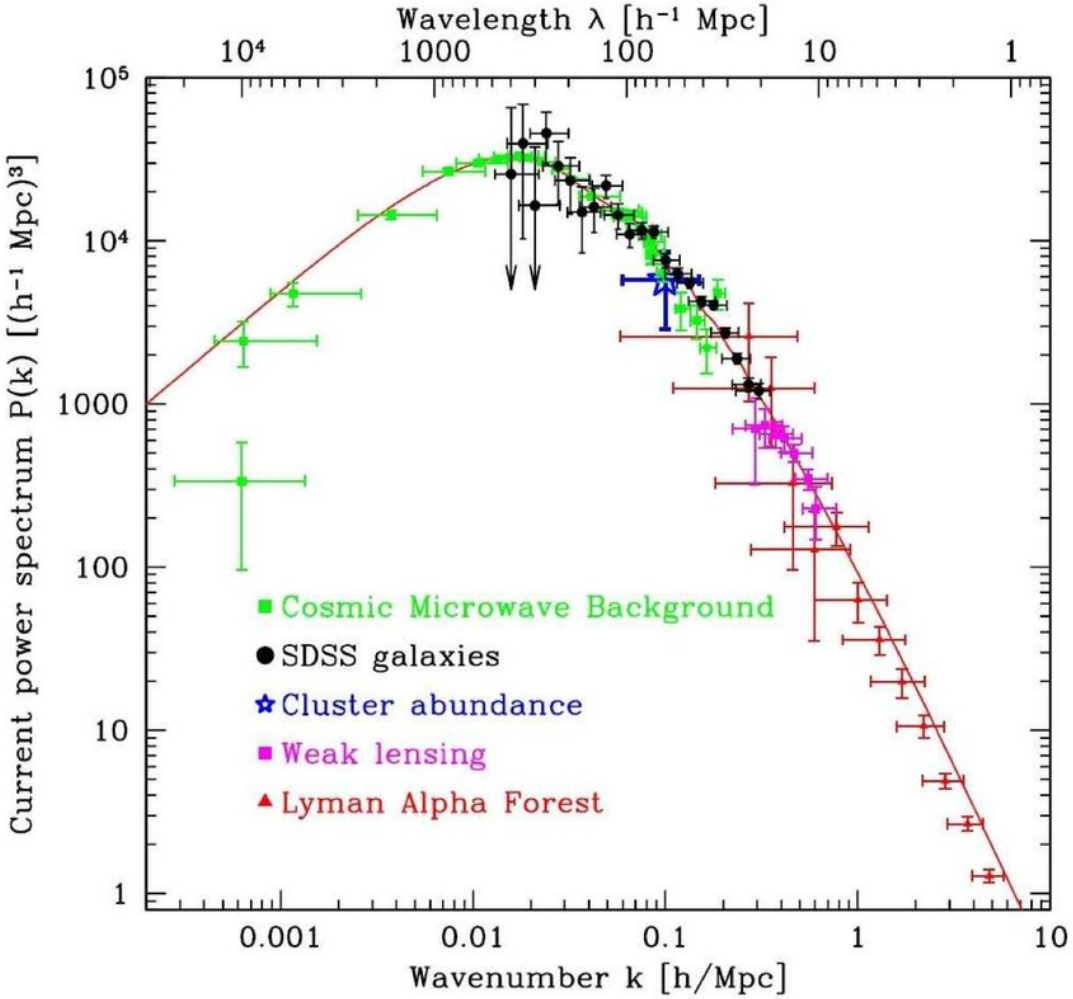

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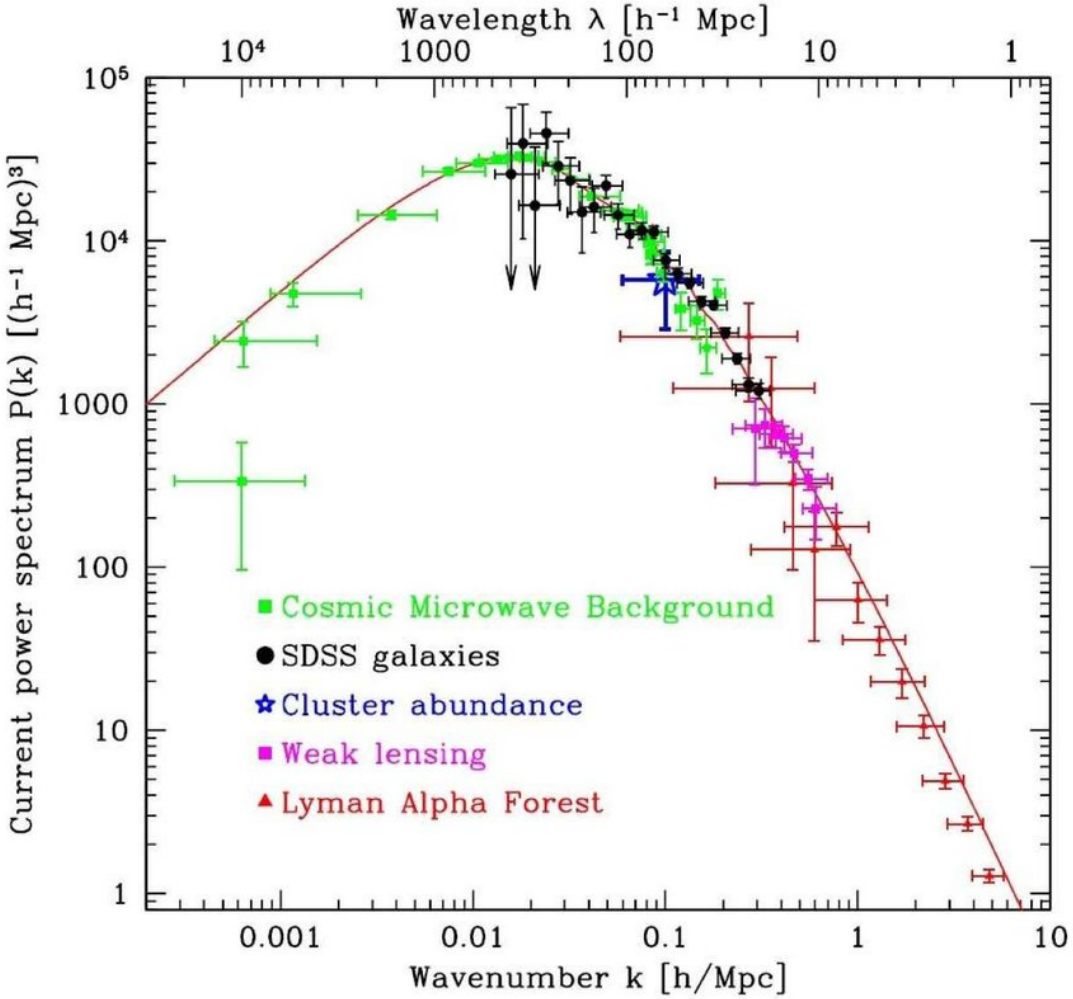

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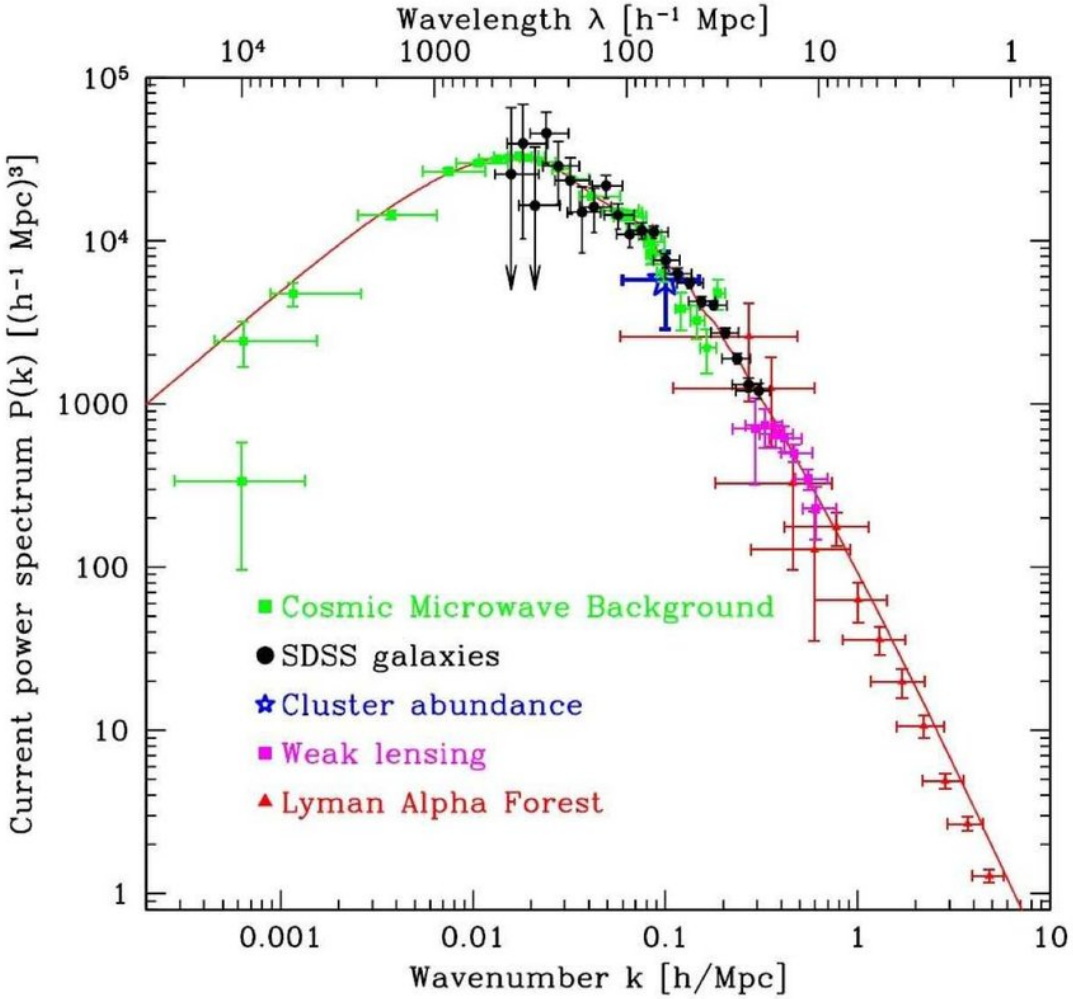

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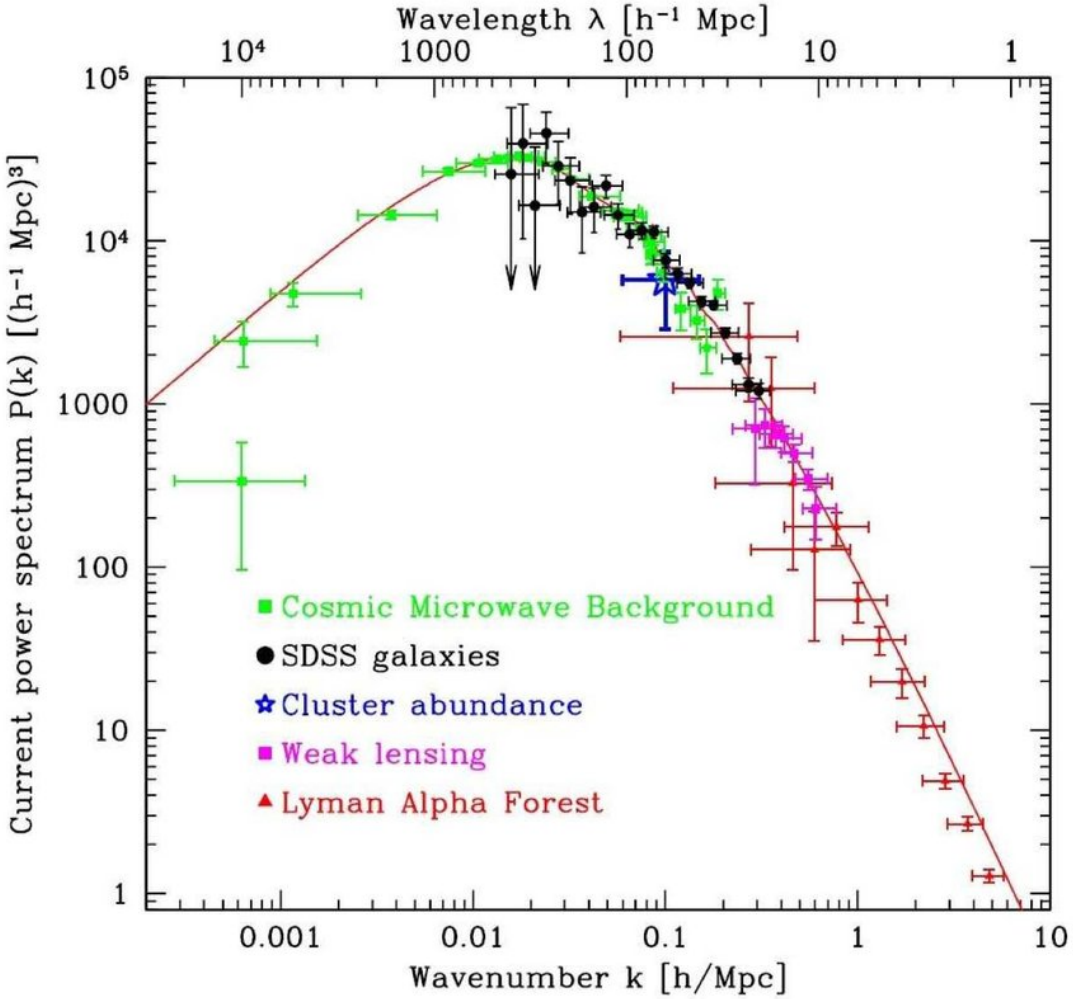

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Scale-Invariant
Matter-Power Spectrum

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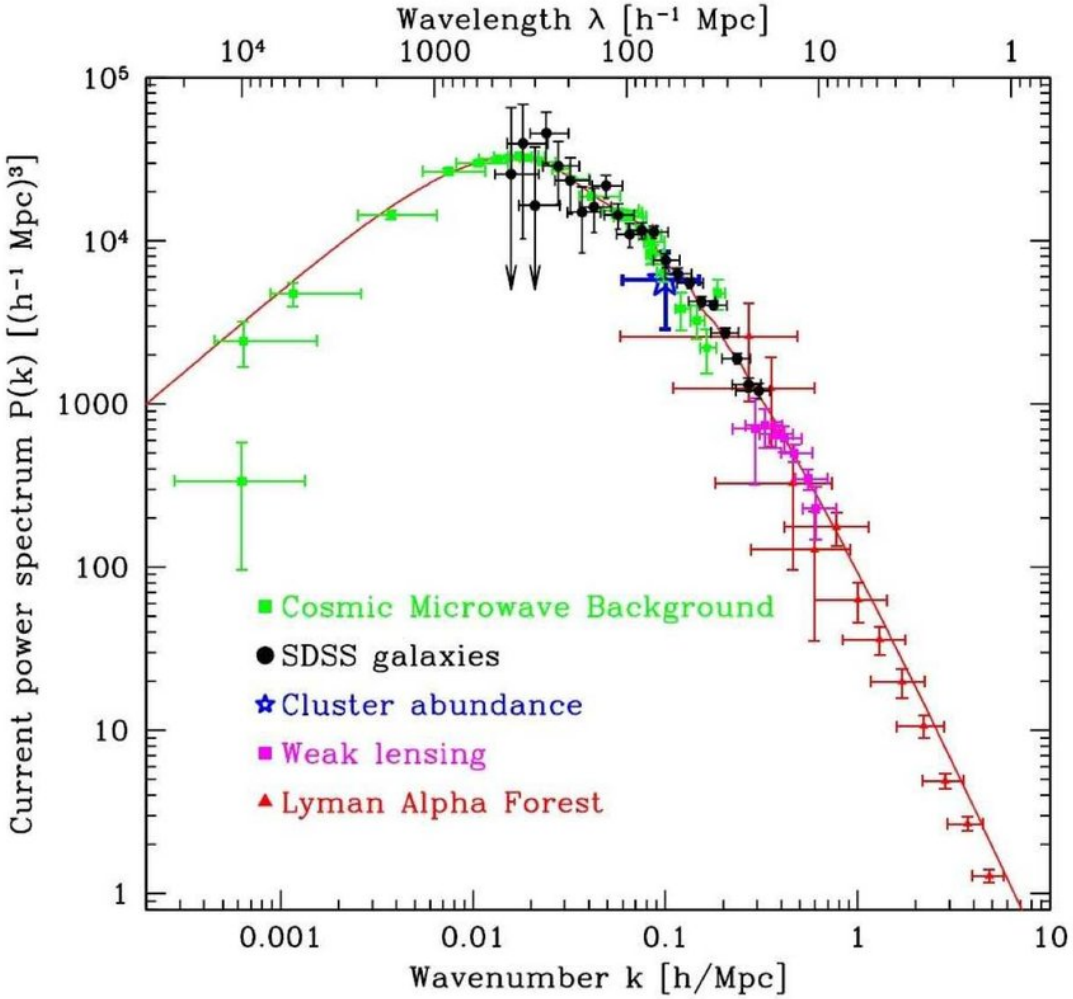

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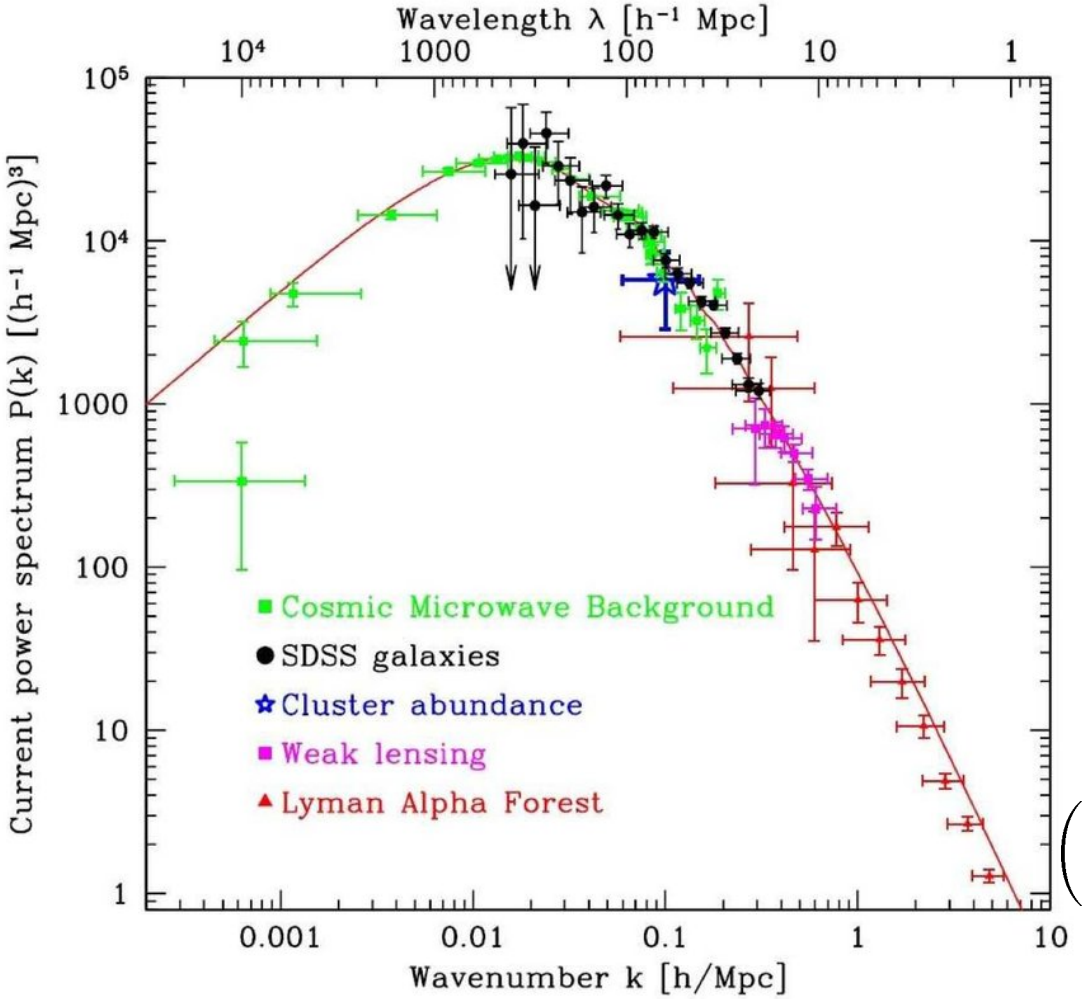

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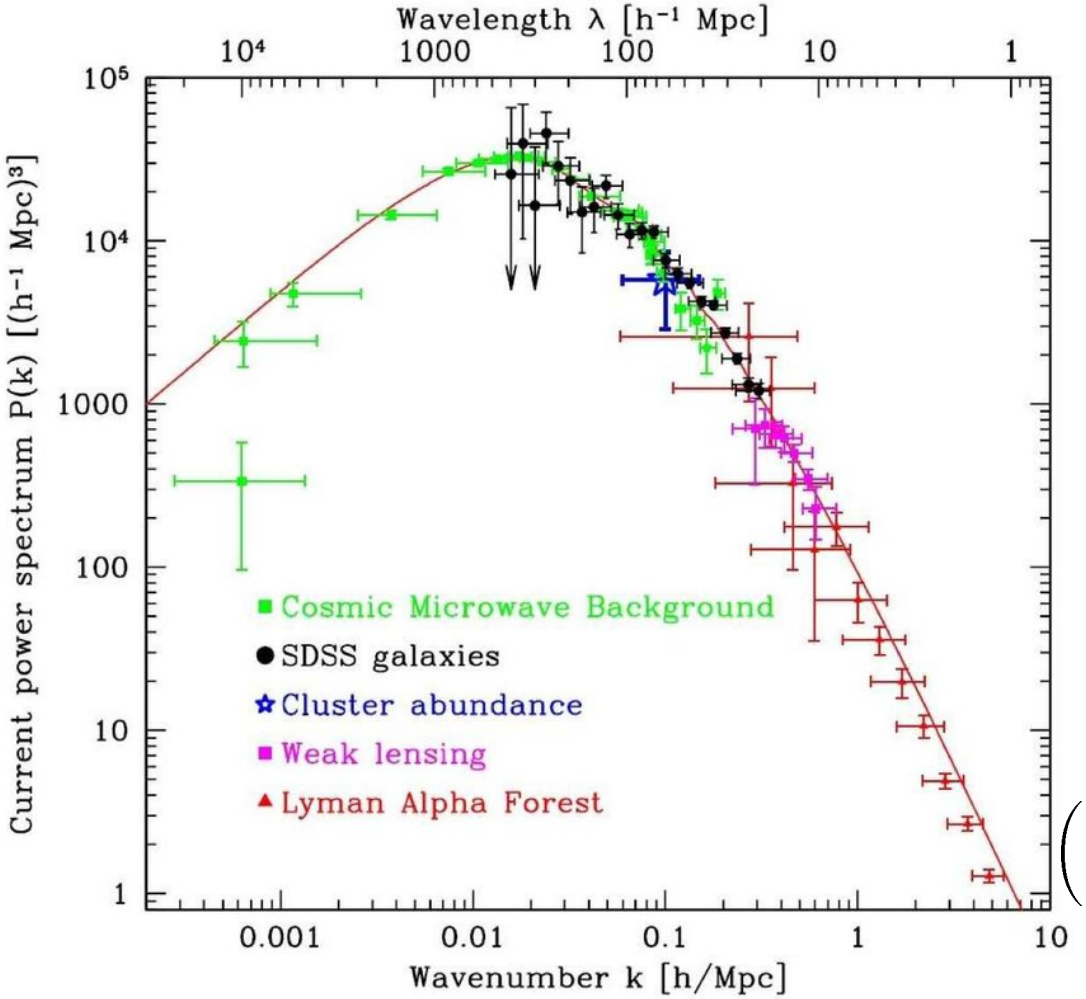
Bounds from the Matter-Power Spectrum (Rough)



[astro-ph/0207047v3 - Tegmark, Zaldarriaga]

$$V \sim \phi^n$$

$$P = \frac{n-2}{n+2}\rho$$

$$\rho \sim R^{\frac{-6n}{n+2}}$$

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$$\Downarrow$$

$$\left(\frac{\delta\rho}{\rho}\right)_{eq} \leqslant 10^{-3} \Rightarrow \left.\frac{\lambda a^4}{m^2 a^2}\right|_{eq} \lesssim 10^{-3}$$

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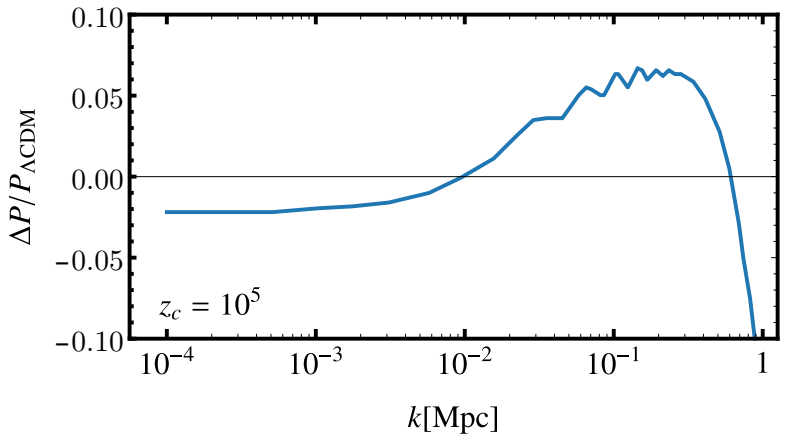
The Rough Cosmological Bound

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

Bounds from the Matter-Power Spectrum (Numerical)

- Matter-Power Spectrum studied for misalignment $\Longrightarrow$
- 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]

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

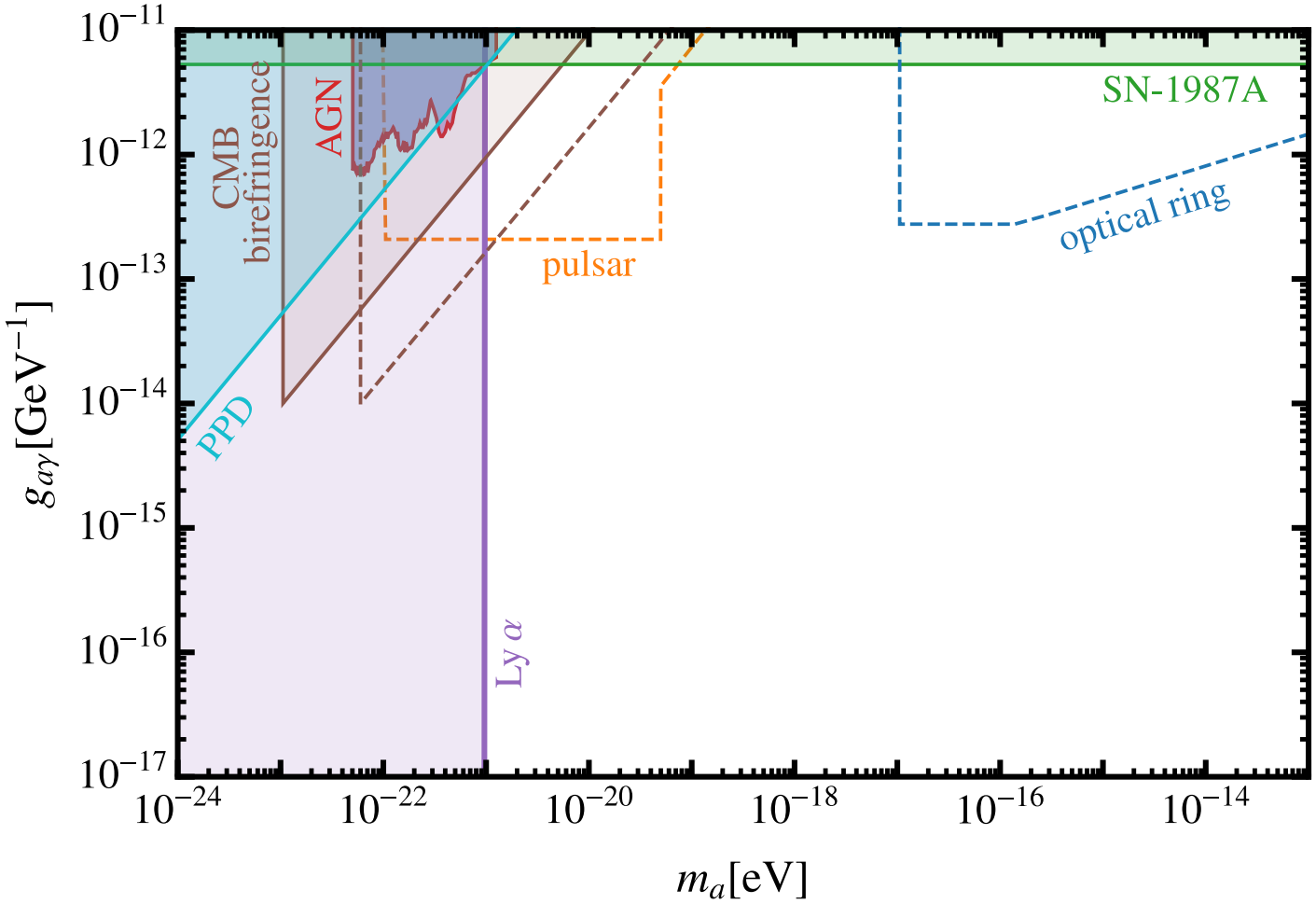
$$a(z) \propto (1+z)^{3/2}$$

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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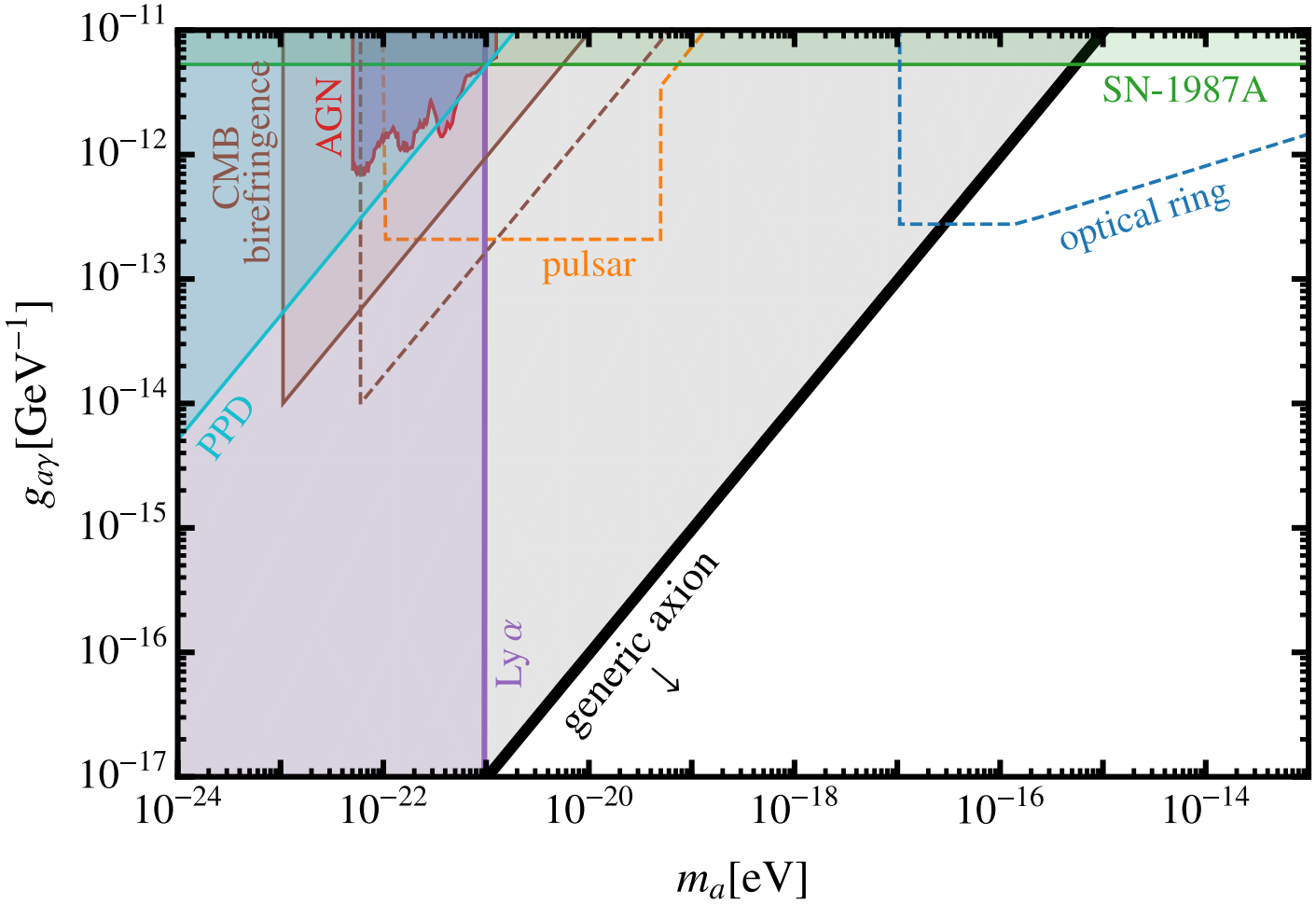

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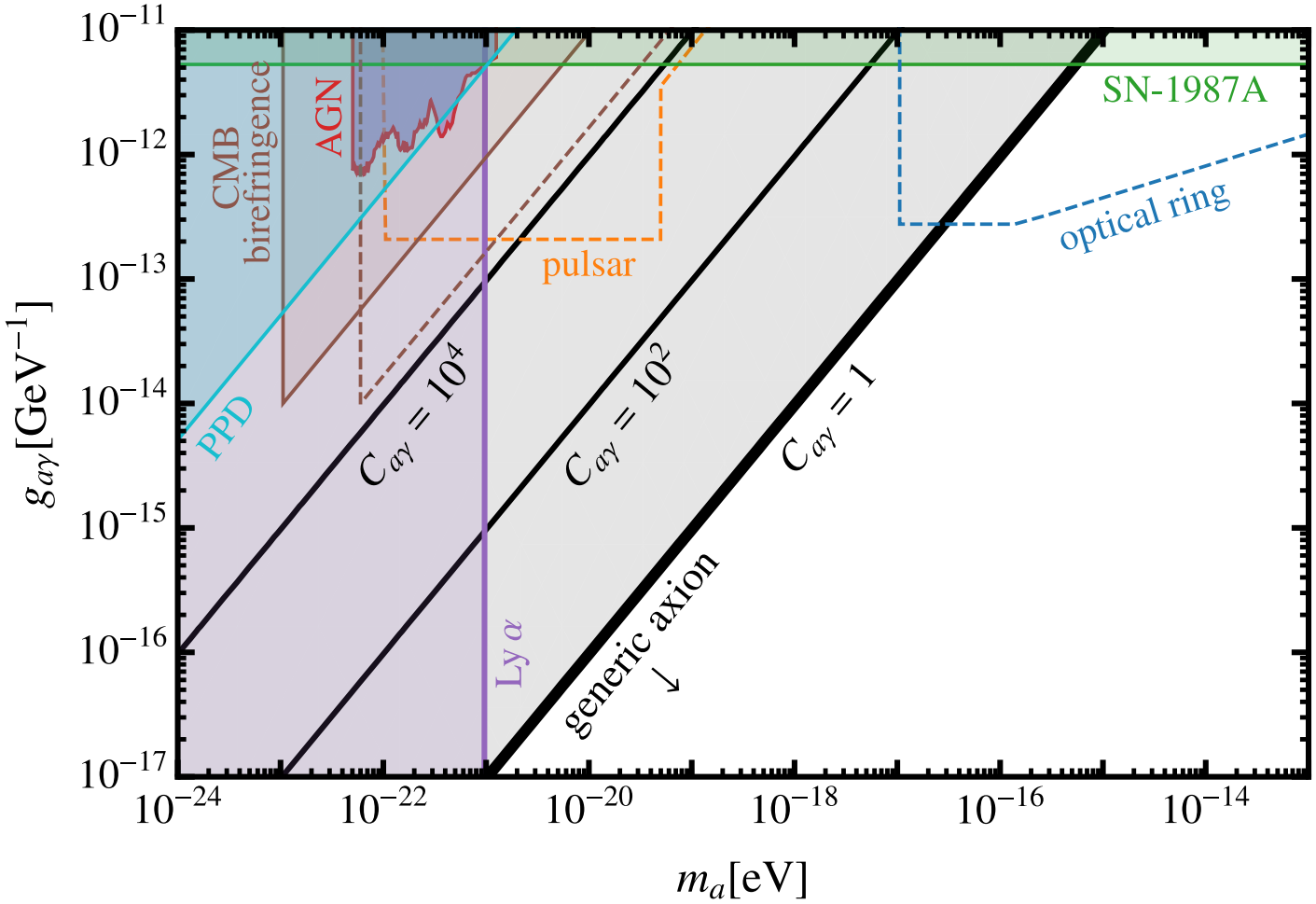

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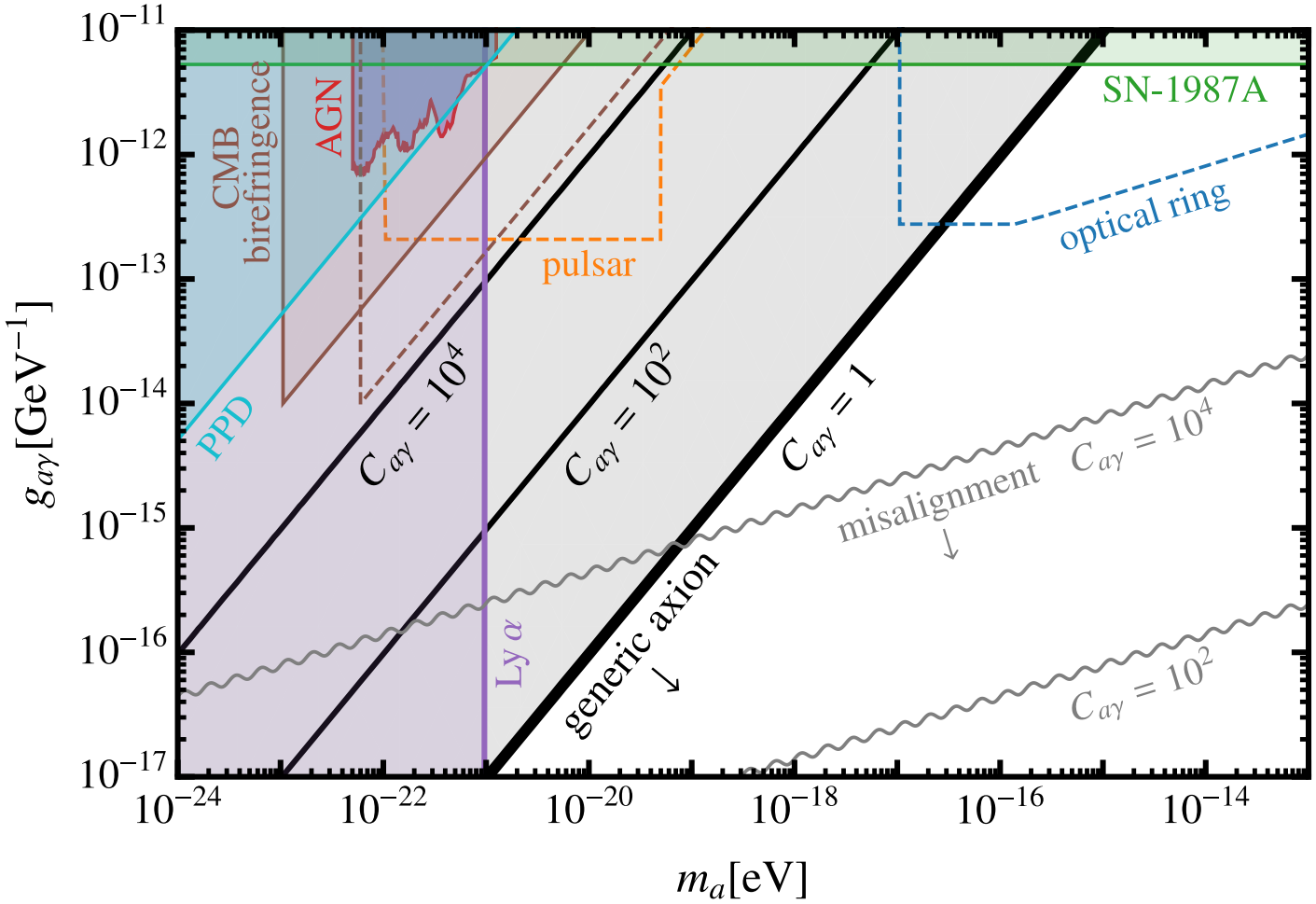
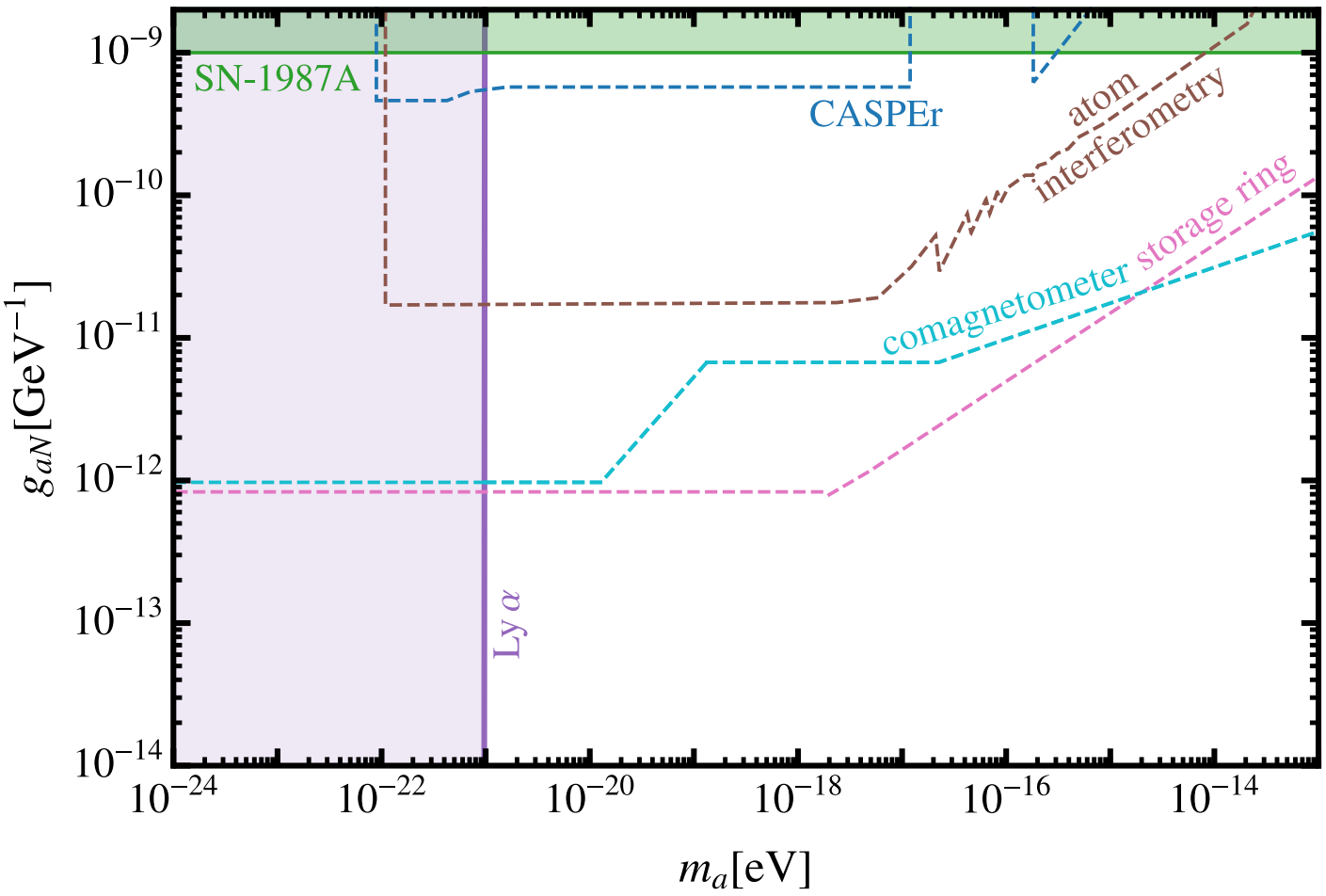


Axion-nucleon parameter space



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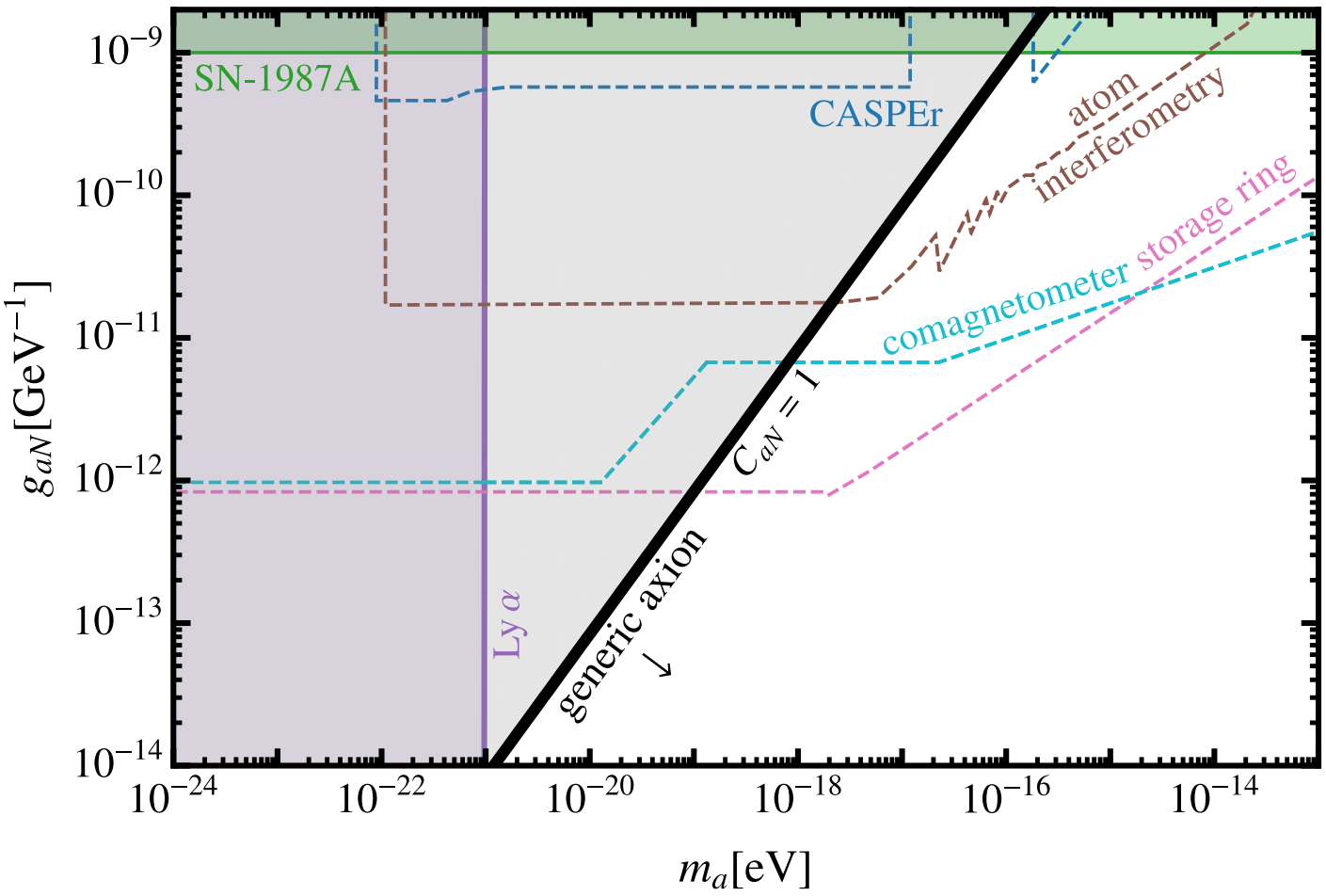

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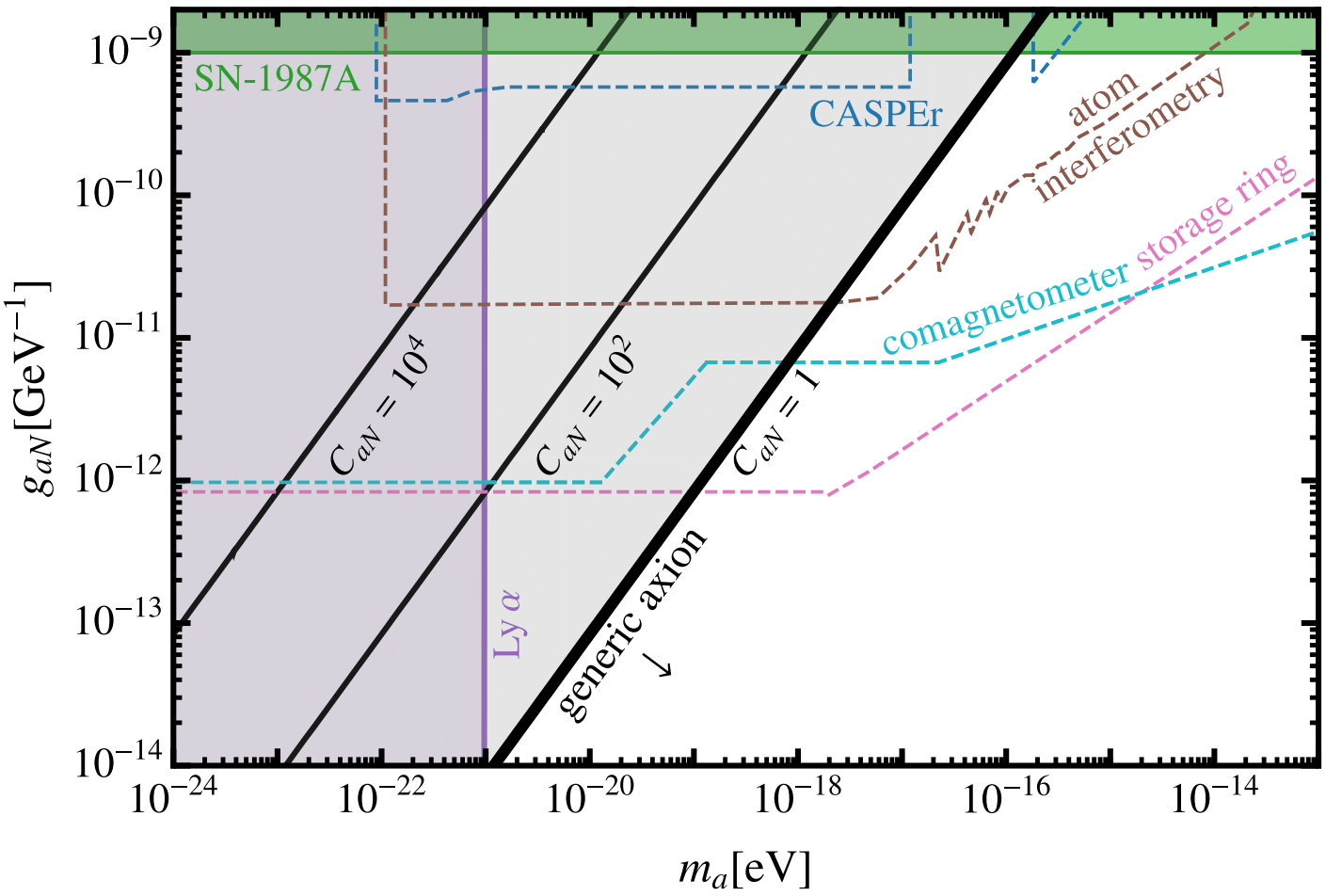

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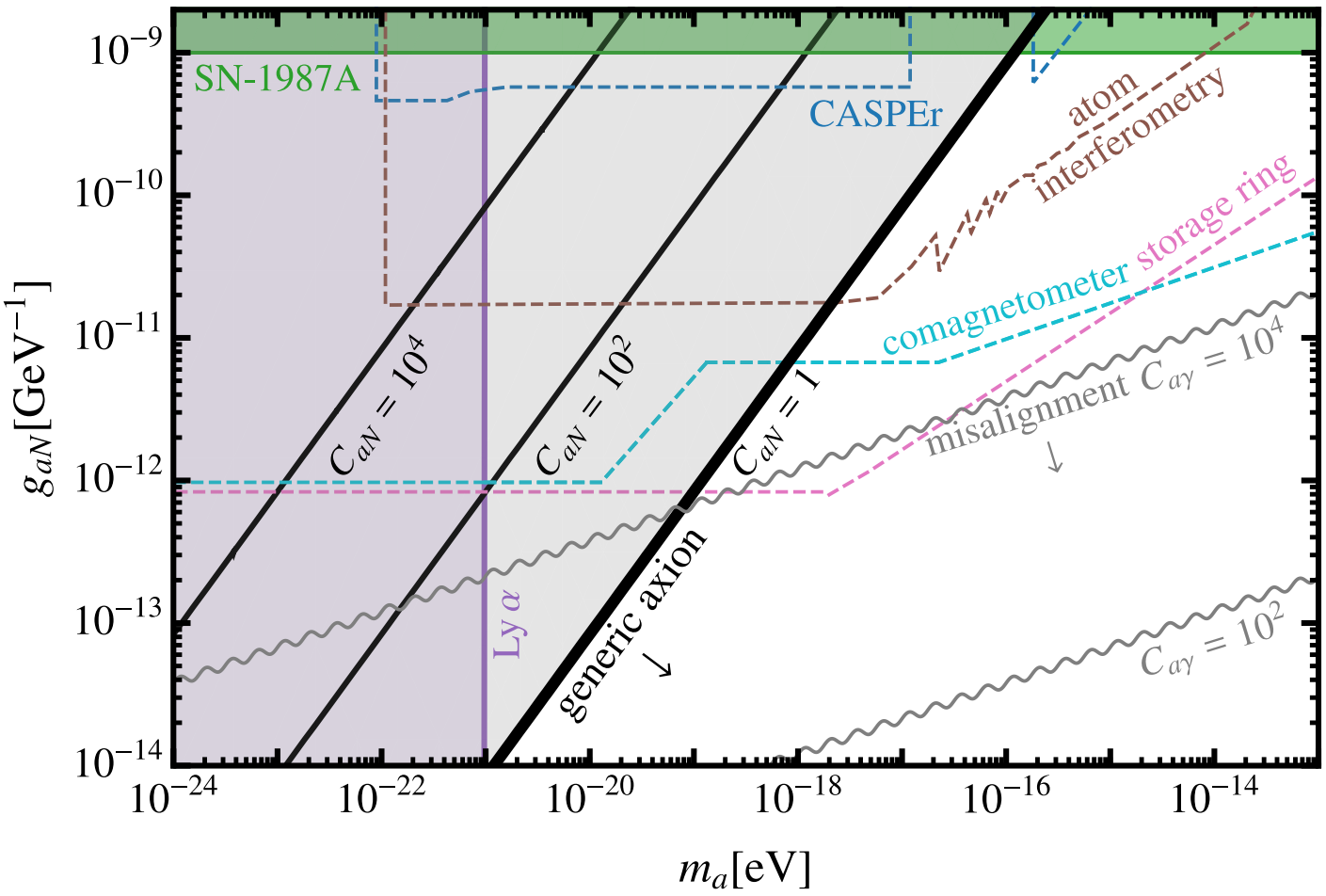
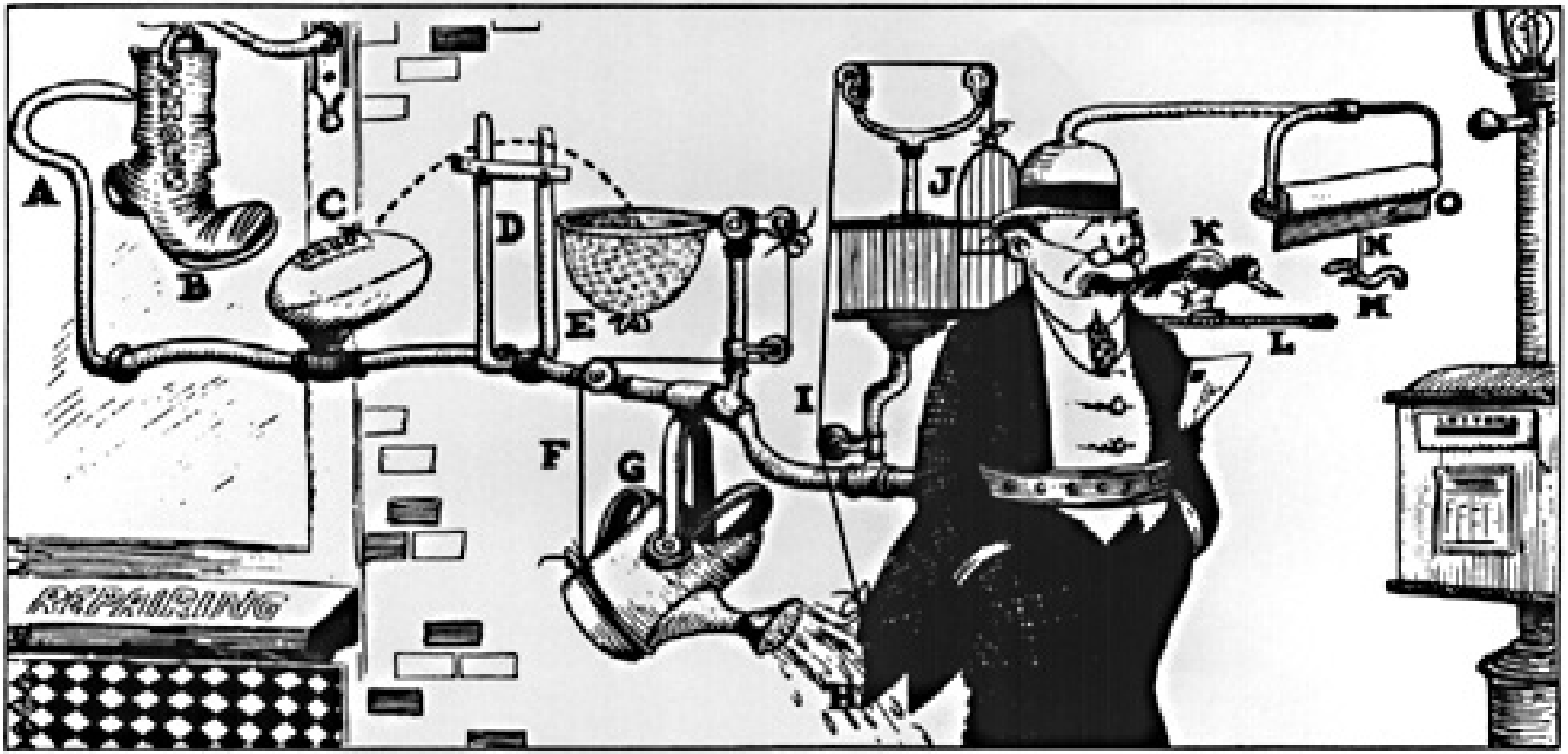


Q:What are experiments looking for?



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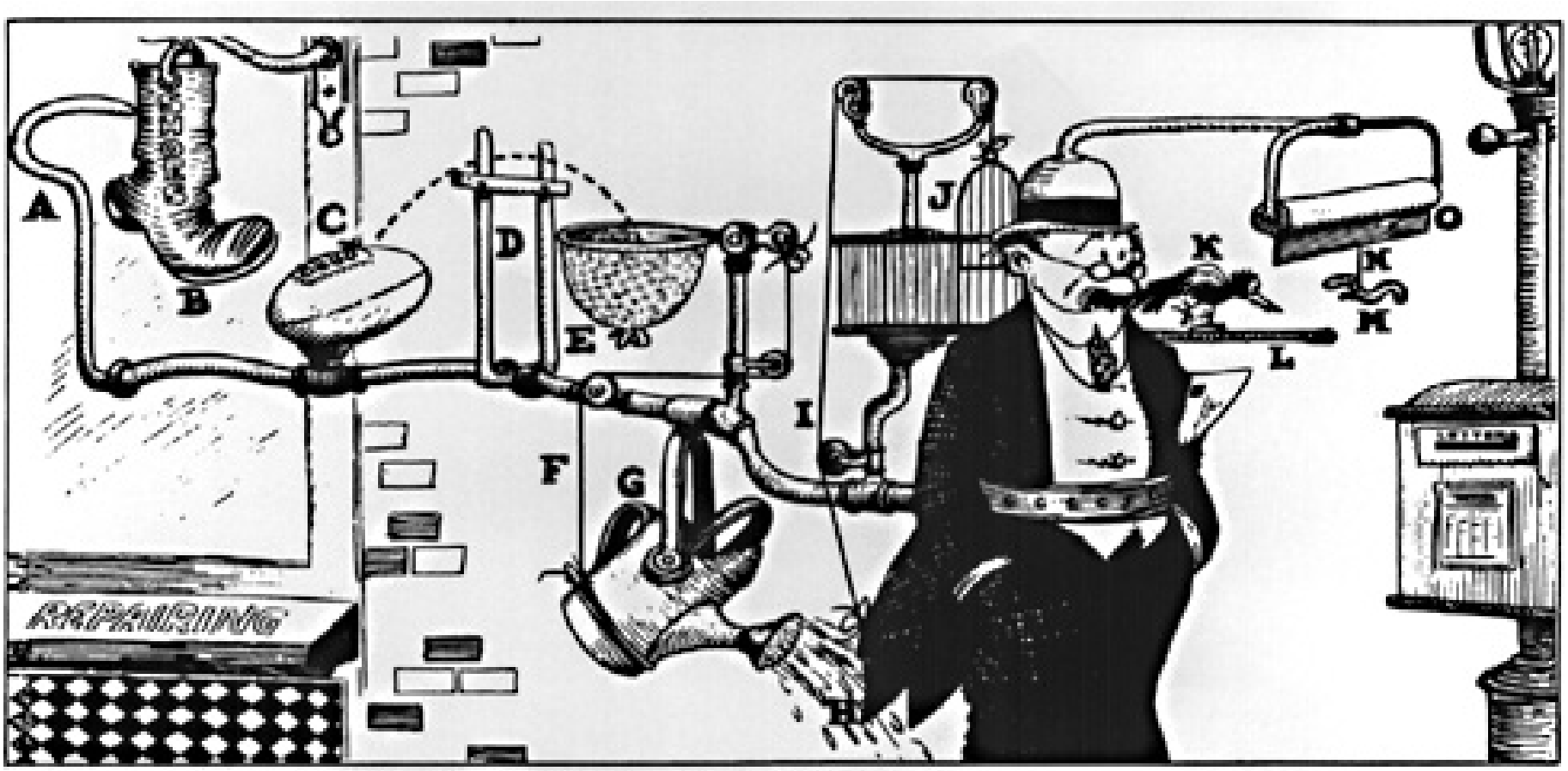

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Rube Goldberg Machine: a machine intentionally designed to perform a simple task in an indirect and overly complicated way

Escaping the Power Spectrum: Can we avoid completely?

- Assumptions:
  - 1. The ultralight dark matter is present until prior to recombination
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- Evade Assumption #2?
  - Dark matter is "just a pseudoscalar"
  - No shift symmetry $\Longrightarrow$ no protection from terms like a^2F^2 & $a^3\tilde{F}F$
  - These terms destabilize the light scalar

Escaping the Power Spectrum: Can we avoid completely?

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

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

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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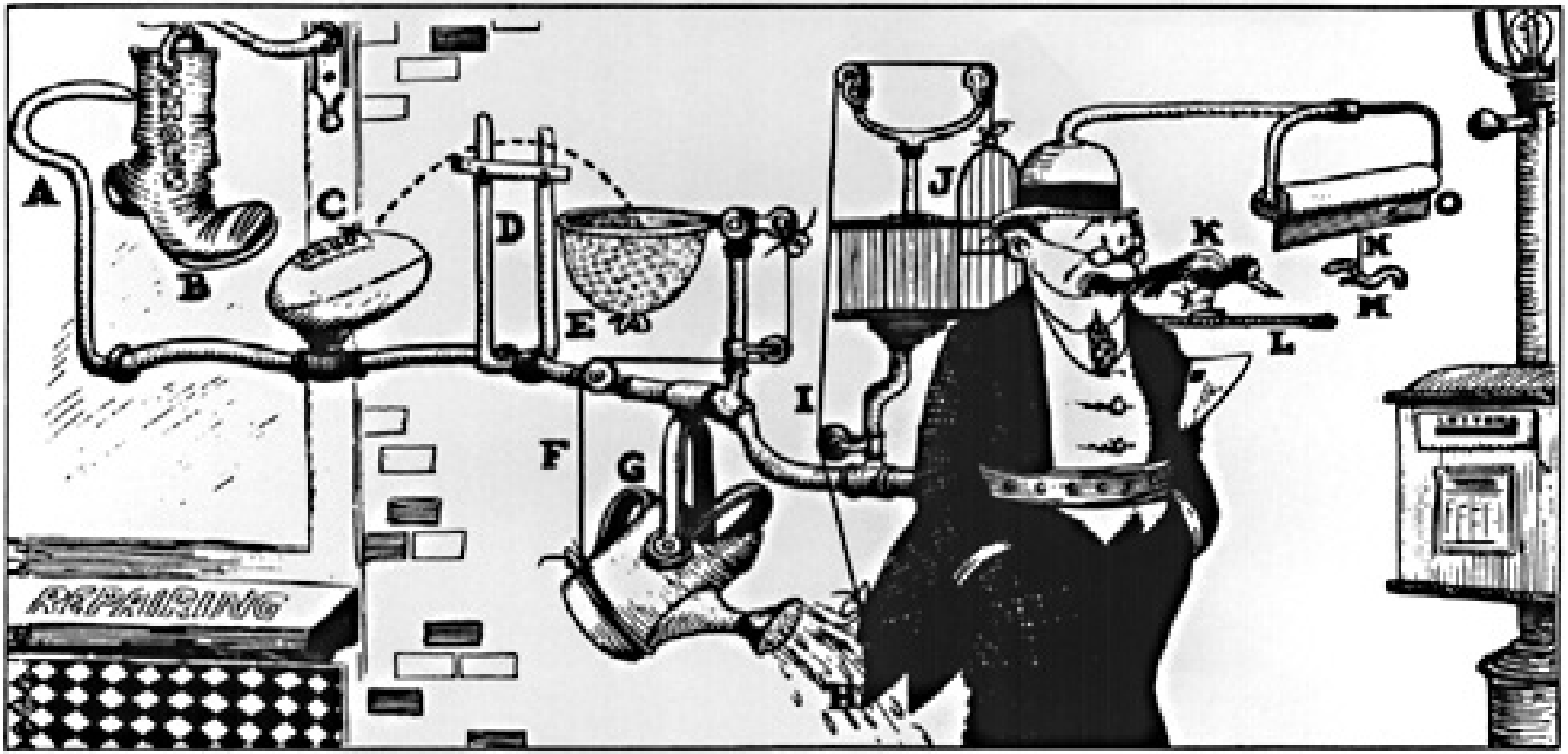

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A: Rube Goldberg (Axion) Model: a model that requires indirect and overly complicated physics to be detectable

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- Simple idea - adjust fermion content:

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

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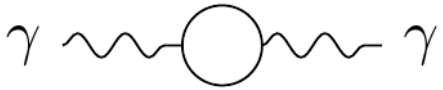

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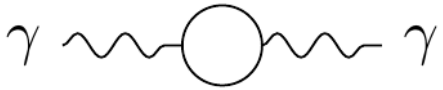

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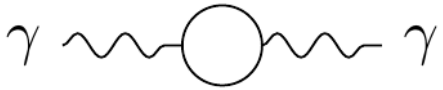

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- Can get $C_{a\gamma} \sim \mathcal{O}(10^2)$
- What about large PQ charges? Large PQ charges result in SM charged states with mass $\lesssim 1$ TeV. $\mathcal{O}(10)$ enhancement possible [1709.06085 - Agrawal et al]

Escaping the Power Spectrum: Kinetic Mixing of Axions

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

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This is not easily done in field theory!

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- Might be able to evade this in string constructions, but no concrete example exists so far [1709.06085 - Agrawal et al]

Based on idea from [1802.10093 - Hook]

- Introduce an axion and N non-abelian gauge sectors $G_{(n)}$ that transform as

$$a \to a + 2\pi F_a/N$$
$$G_n \to G_{(n+1)}$$

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

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- Using simple cosine potential gives $\sum_i \mu^4 \cos\left(\frac{a}{f_a} + \frac{2\pi i}{N} \right) = 0.$
- Need to use more realistic parametrization - find that mass is exponentially suppressed:

$$m_a \sim \frac{1}{2^N} \frac{\mu^2}{f_a}$$

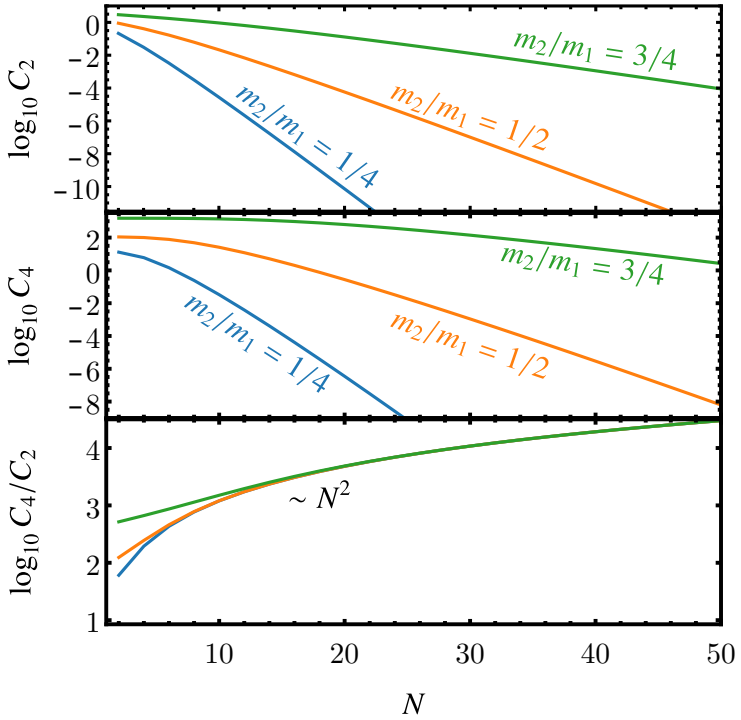
Escaping the Power Spectrum: Discrete Symmetries

- Not whole story - the matter-power spectrum strikes back

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

$$= \frac{1}{2}m_a^2 a^2 - \frac{1}{4!}\lambda a^4 + \cdots$$

$$\left.\frac{\lambda a_0^4}{m_a^2 a^2}\right|_{eq} \sim \frac{\lambda\ \mathrm{eV}^4}{m_a^4} = \left(\frac{\mathrm{eV}^4}{m_a^2}\frac{C_{a\gamma}^2}{f_a^2}\right)\frac{C_4}{C_2}$$



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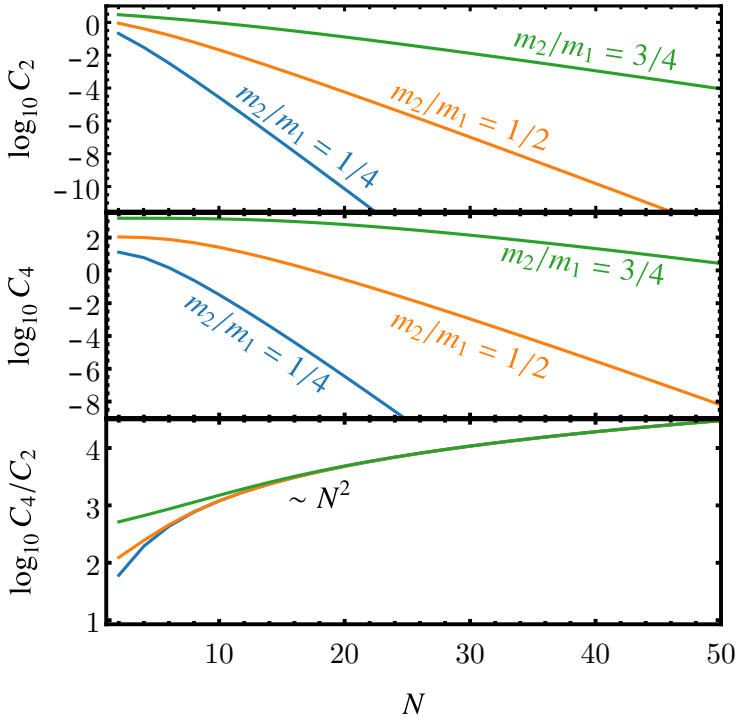

Large enhancement give large deviations in matter-power spectrum

Escaping the Power Spectrum: Clockwork

- N axions a_i & N non-abelian gauge sectors $G_{(i)}$ with Lagrangian

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

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$$V \simeq \sum_{i=1}^{N-1} \mu_{i+1}^4 \cos\left(\frac{\beta_i a_1}{F_i} + \frac{a_{i+1}}{F_{i+1}}\right) + \mu_1^4 \cos\frac{a_1}{F_1}$$

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- Integrating out heavy axions

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

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

Escaping the Power Spectrum: Clockwork

- N axions a_i & N non-abelian gauge sectors $G_{(i)}$ with Lagrangian

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

$$V \simeq \sum_{i=1}^{N-1} \mu_{i+1}^4 \cos\left(\frac{\beta_i a_1}{F_i} + \frac{a_{i+1}}{F_{i+1}}\right) + \mu_1^4 \cos\frac{a_1}{F_1}$$

- Integrating out heavy axions

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

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

Even for modest β_i, large enough N gives significant enhancement

Escaping the Power Spectrum:Clockwork Phenomenology

- $N-1$ heavy axions may be populated in the early universe (misalignment, thermal)
- Light composite sector should exist with mass scale $\mu_1 \sim \sqrt{m_a f_a}$
- Effectiveness of clockwork:
  - From the EFT perspective, clockwork seems to allow for arbitrarily large enhancement
  - Does this hold for UV completions?
  - Perturbative Heterotic String models have a rank $16-4=12$ gauge group to use for clockwork.

Conclusions

- The matter-power spectrum places strong constraints on ultralight axion dark matter models
- Not an obvious, viable method to evade this bound in vanilla axion models
- Can you model build the bound away?
  - Large Charges/Lots of fermions - limited effectiveness
  - Kinetic mixing - doesn't seem to work from the EFT perspective, maybe string constructions could work.
  - Using discrete symmetry - matter-power spectrum bound gets stronger, not viable
  - Clockwork - seems to work. Unlimited effectiveness from EFT perspective, limited effectiveness in string theory?
- Next: Neutrinophilic/majoron ultralight axion dark matter models.