CMB Constraints on Mini-charged Particles

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arXiv:0909.0649

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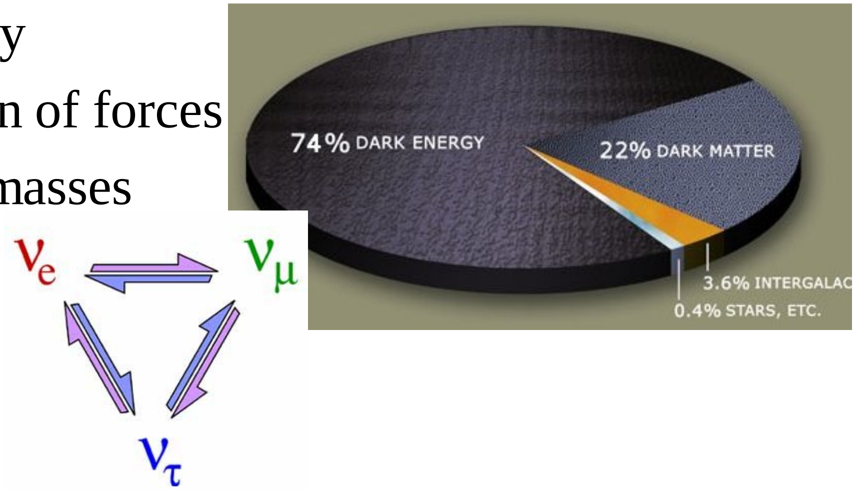
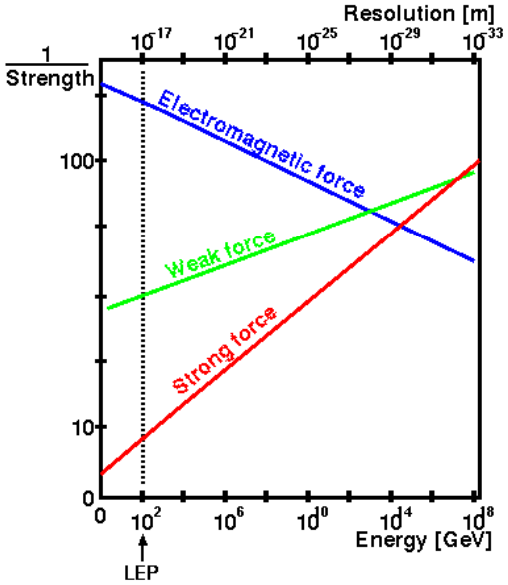
Introduction

- The standard model, despite its successes, is incomplete
- Evidence from:
  - Cosmology
  - Unification of forces
  - Neutrino masses
  - ...





- Extensions of the standard model predict
  - Massive particles
  - Light, weakly interacting particles
- A low energy window onto new physics?

Mini-charged Particles

- Mini-charged particles (MCPs) have tiny (not quantised) charge
- Generic in extensions of the standard model with a hidden U(1)
  - Kinetic mixing between visible and hidden photons (Holdom, 1986)

$$\mathcal{L} = -\frac{1}{4}\tilde{F}_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{4}\tilde{B}_{\mu\nu}\tilde{B}^{\mu\nu} - \frac{\sin\chi}{2}\tilde{B}_{\mu\nu}\tilde{F}^{\mu\nu} + \tilde{e}j^{\mu}_{\rm em}\tilde{A}_{\mu} + e_h j^{\mu}_{\rm h}\tilde{B}_{\mu},$$

  - induces electric charge for hidden sector particles

$$\epsilon = (e_h/e)\tan\chi$$

- Hidden photon can be consistently decoupled to give just photons and MCPs $e_h \to 0$
  - Brane world scenarios with just MCPs (Batell & Gherghetta, 2006)

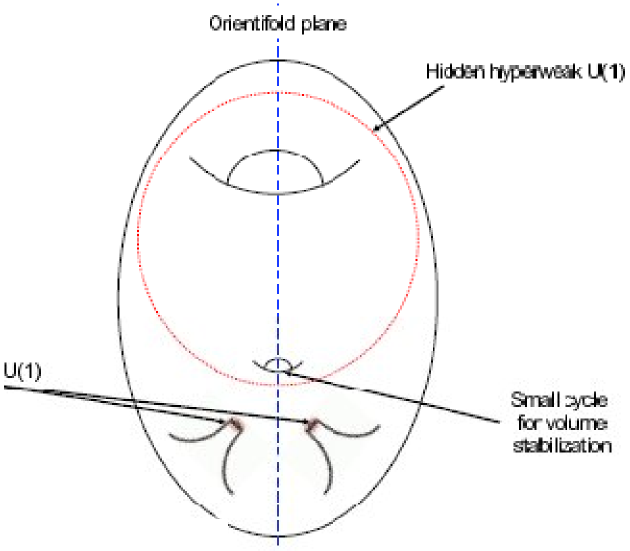
Explicit example:
LARGE volume string models

- String scale is given by $M_P^2 = \frac{4\pi}{g_s^2}\mathcal{V}M_s^2,$
  - LARGE volume $\mathcal{V} = V_6 M_s^6$

(C. P. Burgess et. al. 2008)

- Hidden gauge groups live on a D7 brane wrapped around four compact dimensions
  - gauge coupling $g^2 = \frac{2\pi g_s}{\mathcal{V}_4} \sim \frac{2\pi g_s}{\mathcal{V}^{\frac{2}{3}}},$

$$e_h \sim \begin{cases} 10^{-4} & \sim 10^{-3}\, e \quad \text{for} \quad \mathcal{V} \sim 10^{12} \\ 10^{-10} & \sim 10^{-9}\, e \quad \text{for} \quad \mathcal{V} \sim 10^{27} \end{cases}$$



- Kinetic mixing $\chi \sim \frac{e e_h}{6\pi^2}.$

$$|\epsilon| = \left|\frac{e_h \chi}{e}\right| \sim \frac{e_h^2}{6\pi^2} \sim \begin{cases} \text{few} \times 10^{-10} & \text{for} \quad \mathcal{V} \sim 10^{12} \\ \text{few} \times 10^{-20} & \text{for} \quad \mathcal{V} \sim 10^{27} \end{cases}$$

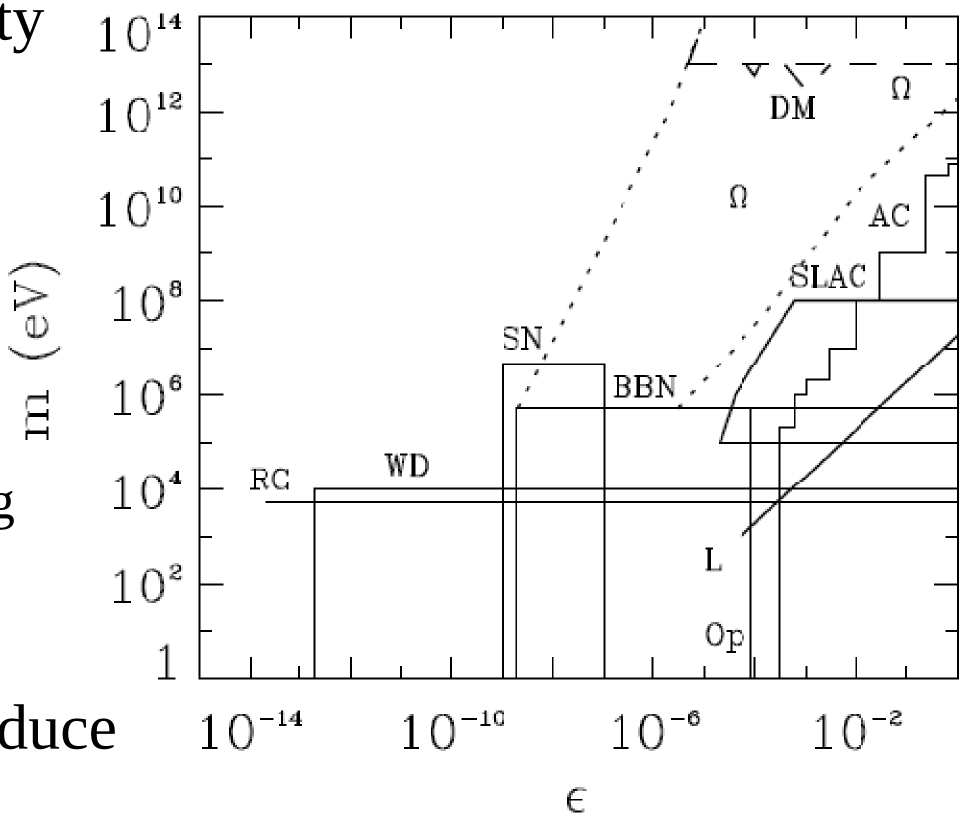
(Goodsell, Jaeckel, Redondo & Ringwald, 2009)

Constraints on MCPs

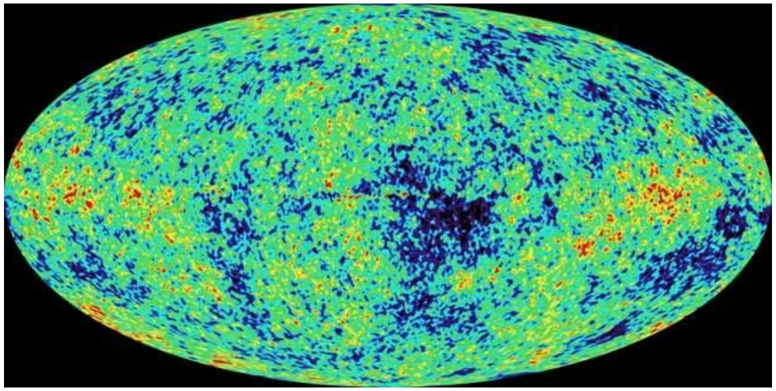
- Constraints from high density regions can be avoided in certain MCP models

  (Masso, Redondo 2000)

- Want new constraints from low density environments
  - directly relevant for upcoming optical searches
- Photons passing through magnetic fields can pair produce real and virtual MCPs
  - can search for this in high precision optical experiments



CMB constraints



- Precision observations of the CMB give information about structure and content of universe
  - Can constrain new physics that interacts with photons
- CMB photons also produce MCPs when they pass through magnetic fields in e.g. galaxy clusters
  - MCP contribution to the Sunyaev-Zel'dovich effect
- A CMB photon interacts with an energetic electron in the plasma of the intra-cluster medium
  - Photons Thompson scattered to higher energies

$$\frac{\Delta T}{T} = f\left(\frac{\omega}{T_{CMB}}\right) \int \frac{n_e T_e \sigma_T}{m_e}\, dl$$

  - Temperature anisotropies typically $\frac{\Delta T}{T} \sim 10^{-4}$

Photon propagation in a magnetic field

- Equations of motion for photon and hidden photon

$$\tilde{B} = B - \tan\chi A,$$

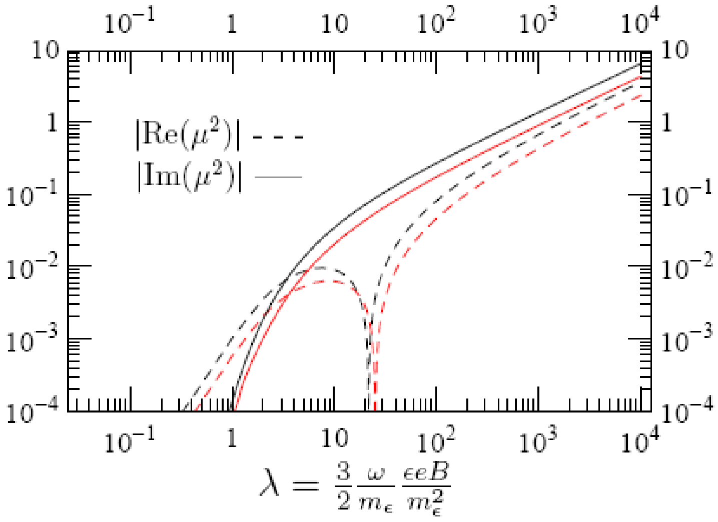
$$\left[(\omega^2 + \partial_z^2)\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} - \begin{pmatrix} \omega_{\mathrm{P}}^2 + \mu^2\chi^2 & -\mu^2\chi \\ -\mu^2\chi & \mu^2 \end{pmatrix}\right]\begin{pmatrix} A \\ B \end{pmatrix} = 0,$$

- Propagating eigenstates

$$V_+(t,z) = \begin{pmatrix} 1 \\ -a \end{pmatrix} e^{i(\omega t - k_+ z)}$$

$$V_-(t,z) = \begin{pmatrix} a \\ 1 \end{pmatrix} e^{i(\omega t - k_- z)},$$

$$a = \frac{\mu^2}{\omega_{\mathrm{P}}^2 - \mu^2}\chi$$



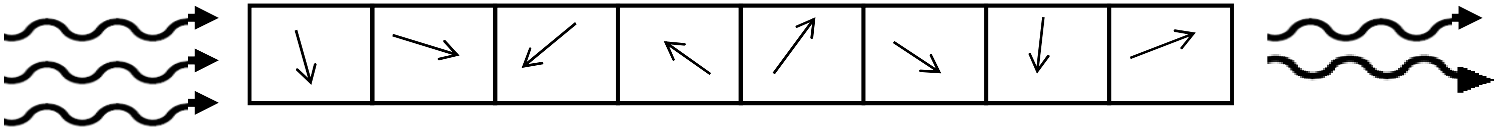
- In the small kinetic mixing limit probability of photon survival

$$P_{\gamma\to\gamma}(z) = 1 - 2\mathrm{Re}\{a^2\} - \chi\frac{z\omega_P^4}{\omega}\mathrm{Im}\{a\} + 2\mathrm{Re}\{a^2 e^{-iz(\omega_P^2-\mu^2)/2\omega}\} + \mathcal{O}(\chi^4).$$

  - If phase is large $P_i(z) = 1 - p_i - q_i z$

The MCP S-Z effect

- Cell magnetic field model for the cluster
  - magnetic field of equal magnitude but random orientation in each domain



- Compute the effect of MCPs averaged over all paths
  - At the end of the N-th domain the photon flux is

$$I_N = I_0\Big(1 - \langle p\rangle - N\langle q\rangle L + \mathcal{O}(N^2\langle q\rangle^2)\Big)$$

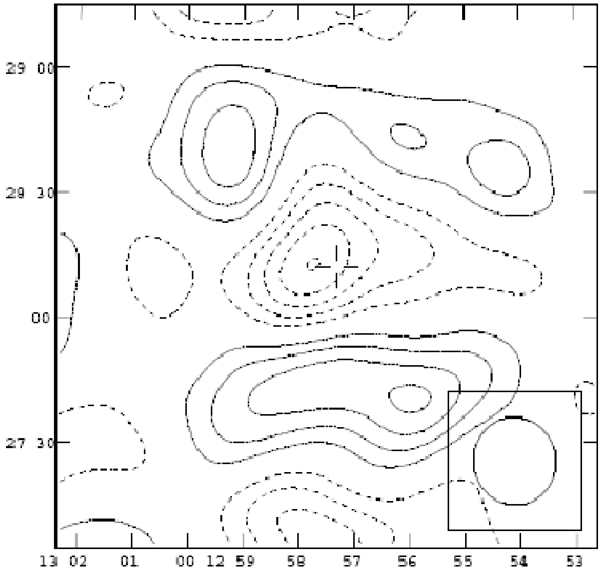
- Temperature anisotropy

$$\frac{\Delta T}{T} = \frac{1-e^{-x}}{x}\frac{\Delta I}{I_0}; \qquad x = \omega/T_{CMB}$$

The Coma Cluster

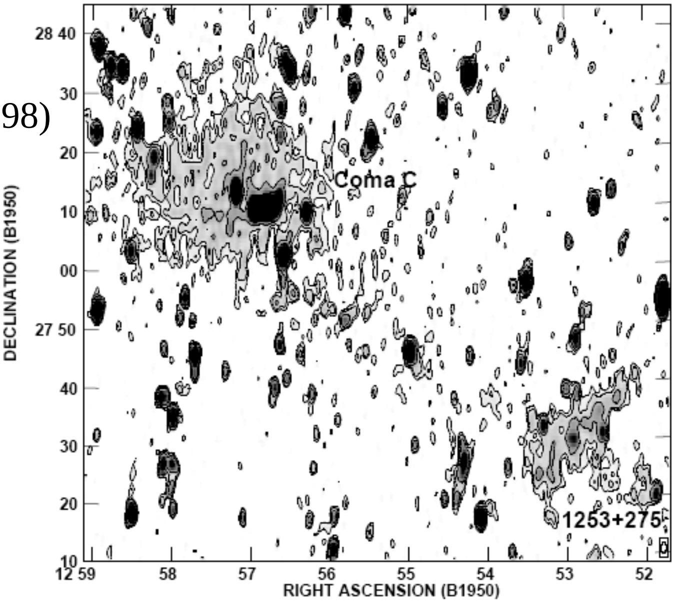
- Need a cluster for which the magnetic field and S-Z effect are understood: Coma Cluster
  - S-Z effect
    $\Delta T = -32 \pm 79\ \mu\mathrm{K}$
    at $214\ \mathrm{GHz}$ from MITO

–Field strength $B \approx 1 \times 10^{-11}\ \mathrm{T}$
–Domain size $L \approx 10\ \mathrm{kpc}$
–Cluster size $1\ \mathrm{Mpc}$
–Plasma frequency $\omega_P = 10^{-12}\ \mathrm{eV}$

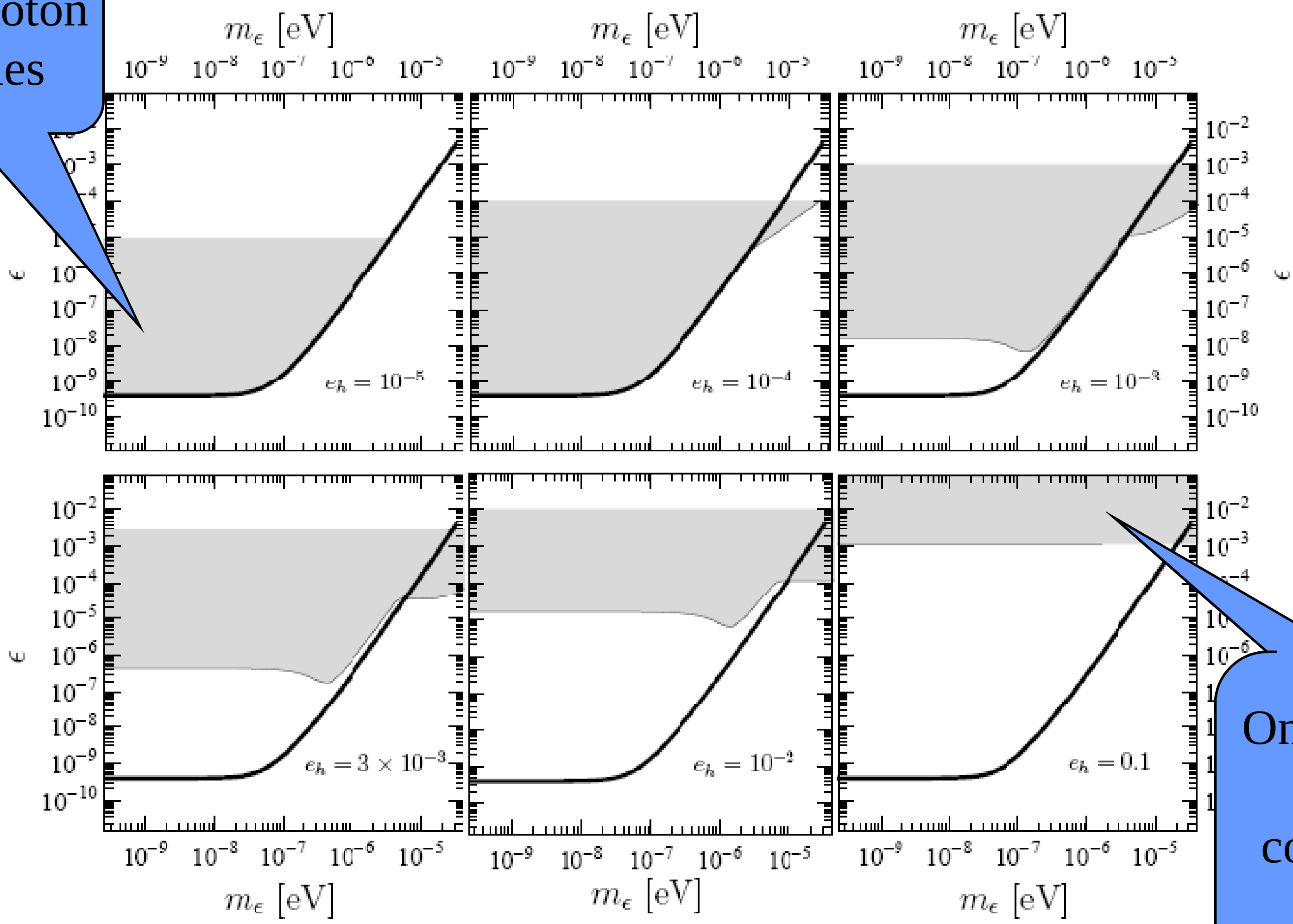


(Lancaster et al 2004)

(Feretti et al 1998)



Constraints from the Coma Cluster

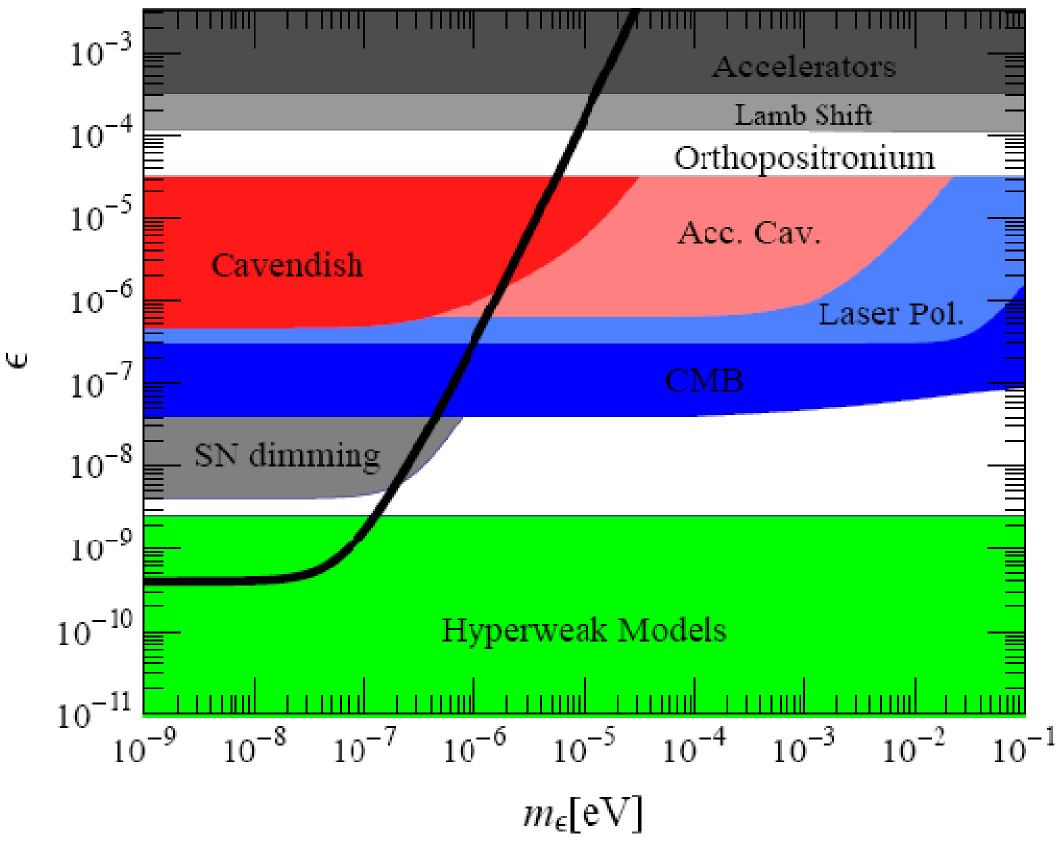


Hidden photon decouples

Only hidden photon component damped

Constraints on LARGE volume models

- LARGE volume string scenario with hyperweak U(1) and string scale $M_s \lesssim 10^{11}\ \mathrm{GeV}$



Conclusions

- MCPs are generic in extensions of the standard model with hidden U(1)s
- Photons propagating in magnetic fields can pair produce real or virtual MCPs
- For CMB photons passing through the magnetic fields of galaxy cluster this looks like a contribution to the Sunyaev-Zel'dovich effect
- Observations of the Coma cluster give new constraints on MCPs
  - Probes the hyperweak gauge interactions of the LARGE volume scenario