Chameleon Forces

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"Workshop on Dark Forces"

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Outline

- intro to chameleons
  - scalars
  - vectors
- Can the parameter space for a vector be expanded via chameleons?
  - applications to “light dark matter”, hidden sector models of dark matter with light bosons

Environmental dependence of particle properties is not unusual

- ➡ index of refraction
- ➡ K_S regeneration
- ➡ Neutrino MSW effect
- ➡ Quasi particles in condensed matter
- ➡ effective mass of photon, (superconductivity)
- ➡ All Standard Model fermion mass terms depend on value of Higgs scalar which varies (e.g. is zero in very early universe)
- ➡ diaelectric, diamagnetic, paramagnetic screening or anti screening

We must not assume that properties of exotic particles are independent of their environment

Spinless Chameleon model

Barrow, Mota, Khoury, Weltman, Gubser, Brax, van de Bruck, Davies,

...Feldman, A.E.N

Motivation: hiding very light scalars or pseudoscalars
from long range force experiments

Chameleon bosons are challenging to detect because their effective mass and couplings depend on the local environment

Simple example of a spinless Chameleon

“Chameleon term”

- $\mathcal{L}=(\partial\varphi)^2/2\underbrace{-(m^2/2)\varphi^2-(\mu/3)\varphi^3-(\varepsilon/4)\varphi^4}_{\text{Potential}}+g\varphi\rho$

source for φ

- assume potential minimized at $\varphi=0$ in vacuum
- $(\mu/3)\varphi^3$ term never large relative to other terms
- for simplicity neglect μ

“effective φ mass”

- static equation of motion: $\nabla^2\varphi=-g\rho+(m^2+\varepsilon\varphi^2)\varphi$

effective mass of scalar chameleon

- ➡ chameleon screens itself, does not mediate strong new long range force
- ➡ for negligible m, φ falls exponentially until $\varphi \sim 1/(\varepsilon^{1/2}r)$
- ➡ effective coupling is small, suppressed compared to gravity by factor $\sim m_{pl}/(M\varepsilon^{1/2})$ *
(ε is the coefficient of φ^4, M the source mass)
- ➡ coupling depends on mass M, not composition of source
- ➡ equivalence principle violation experiments designed with equal mass objects with large source masses
can not find chameleon scalar forces

* provided $\varepsilon > (m_{pl}/\beta M)^2$, where β is strength relative to gravity, else nonlinearity ignorable

Vector Chameleons

A.E.N. and J. Walsh, 2007

New vector particles?

- ➡ massless vector must couple to conserved current
- ➡ candidates in SM are Q_{em}, B, L
- ➡ can also couple to dark charges
- ➡ ultralight vector couplings to axial currents very constrained
- ➡ red giant cooling constrains couplings of particles lighter than 30 keV
- ➡ supernova cooling constrains couplings of particles lighter than 10 MeV
- ➡ searches for long range forces constrain couplings of particles lighter than eV
- ➡ fixed target, rare decays, g-2, e^+e^- factories constrain lighter than few GeV

Chameleonic U(1) Gauge Force

General effective field theory considerations

- ➡ Order one effects typically require new particles which are lighter than scale of affected physics
  - ➡ For ordinary solids, this implies sub keV mass scalar
  - ➡ For red giants, this means sub 30 keV mass scalar
  - ➡ For supernova, sub 50 MeV mass scalar

“But aren’t light scalars unnatural?”

- ➡Not necessarily.
(very low energy susy in gauge mediation, little Higgs, RS models, composite models, ...)
  - ➡Implies additional light particles
- ➡So What?
(Naturalness of scalar masses is not yet an experimentally established principle. What if theorists are wrong about no finetuning of unobservable quantities?)

Vector Chameleon

- ➡ charge q scalar field s=|s|e$^{i\theta}$
- ➡ gauge field B$_\mu$
- ➡ either sign m^2 ("scalar QED" or "Abelian Higgs model")

$$\begin{aligned}\mathcal{L} &= (\partial_\mu + iqgB_\mu)s^*(\partial^\mu - iqgB^\mu)s - m^2|s|^2 - \frac{\epsilon}{2}|s|^4 \\ &\quad -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - gB_\mu j^\mu\end{aligned}$$

Coupled equations of motion for U(1) gauge field and Charged Scalar

- charge q scalar field $s=|s|e^{i\theta}$
- configuration $\theta=qwt$, $B_i=0$, $i=1,2,3$
- gauge invariant fields $|s|$, $\omega= w+gB_0$
- gauge invariant equations of motion for static configuration

$$\begin{aligned} \nabla^2|s| &= \left(m^2+\epsilon|s|^2-q^2\omega^2\right)|s| \\ \nabla^2\omega &= -g^2\rho+2q^2g^2\omega|s|^2 \end{aligned}$$

gauge field acts as negative m^2

scalar screens gauge field

Three different parameter regimes

1. $|m|>(\epsilon\rho)^{1/3}$,$m^2<0$: Chameleon effect minimal "Usual Abelian Higgs model"
2. $|m|>(\epsilon\rho)^{1/3}$,$m^2>0$: ϵ negligible. Condensate in sufficiently large objects, with $|\omega|<|m/q|$
3. $|m|<(\epsilon\rho)^{1/3}$: High density Chameleon Regime
    - In constant density matter have approximate sol $\omega=\omega_0$

$$\omega_0 \approx \frac{(\epsilon\rho)^{\frac{1}{3}}}{q}$$

$$|s| \approx \left(\frac{\rho}{\epsilon}\right)^{\frac{1}{3}}$$

When is chameleon effect significant for Abelian Higgs model?

- ➡ $|m|>(\varepsilon\rho)^{1/3}$,$m^2<0$: Chameleon effect minimal
- ➡ $|m|<(\varepsilon\rho)^{1/3}$: High Density Chameleon Regime

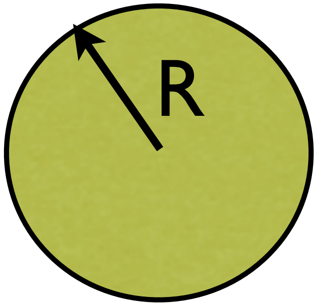
In constant density matter have solution with constant $\omega=\omega_0$

$$\omega_0 \approx \frac{(\epsilon\rho)^{\frac{1}{3}}}{q}$$

$$|s| \approx \left(\frac{\rho}{\epsilon}\right)^{\frac{1}{3}}$$

At high density gauge boson mass proportional to density$^{1/3}$, arbitrarily big

Approximate solution for large objects in “thin shell” chameleon regime



$$\omega_0 \approx \frac{(\epsilon\rho)^{\frac{1}{3}}}{q}$$

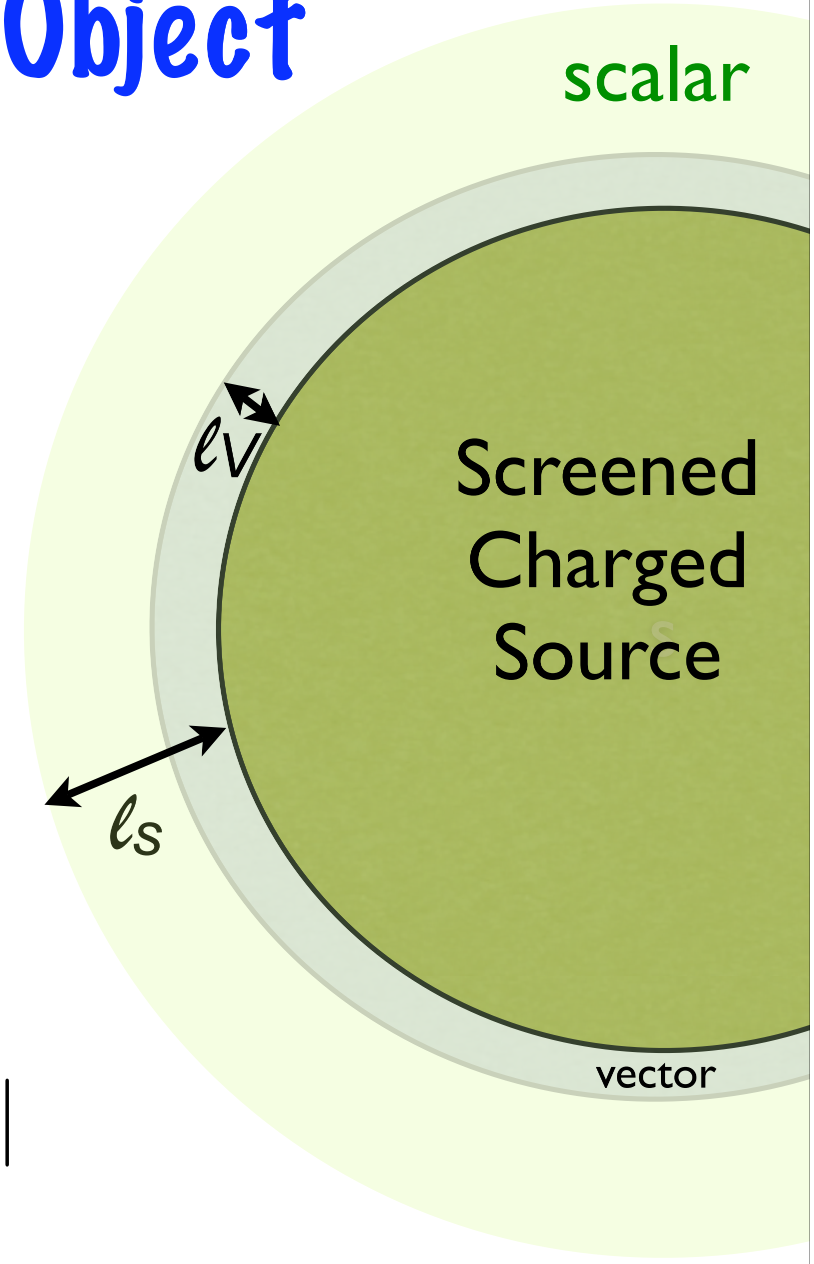
$$|s| \approx \left(\frac{\rho}{\epsilon}\right)^{\frac{1}{3}}$$

➡As long as size R> vector screening length ℓ_V, scalar screening length ℓ_S, fields ≈ constant inside

$$\ell_V = (M_V)^{-1} = (\sqrt{2}qg|s|)^{-1}$$

$$\ell_S \equiv \frac{1}{m_{\mathrm{eff}}} = \frac{1}{\sqrt{m^2 + \epsilon s_0^2}} = \frac{1}{q\omega_0}$$

Thin Shell Near a Large Object



- ➡vector field falls exponentially on scale ℓ_V
- ➡scalar field falls on larger of scales ℓ_S, ℓ_V

$$\begin{aligned} \nabla^2|s| &= \left(m^2+\epsilon|s|^2-q^2\omega^2\right)|s| \\ \nabla^2\omega &= -g^2\rho+2q^2g^2\omega|s|^2\ . \end{aligned}$$

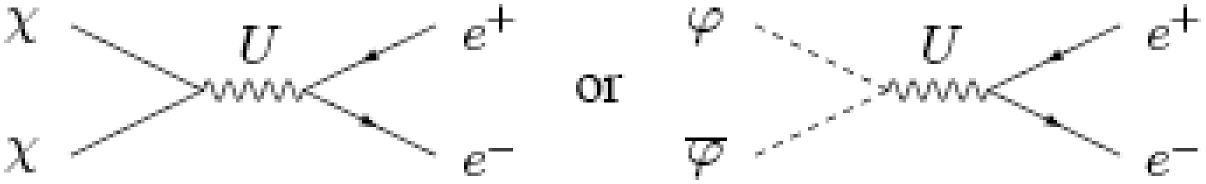
Example: gauge B-L

- ➡ vev of B-L charged scalar gives gauge boson mass (or effective mass in matter)
- ➡ anomaly free in Standard Model with 3 right handed neutrinos
- ➡ earth, ordinary matter has net B-L charge
- ➡ B-L unbroken in vacuum? (if scalar extremely light, positive mass)

Example:
Viable Light Dark Matter?

Fayet, 1980

Boehm and Fayet, 2003



$$\sigma_{ann}\, v_{rel} \sim O(10^{-26}) - O(10^{-27})\ \mathrm{cm}^3\,\mathrm{s}^{-1}$$

- ➡Dark matter of mass (1-10 MeV) proposed for Integral positron signal
- ➡p-wave annihilation for cosmology and gamma constraints requires new light boson

Boehm, Fayet, Silk 2003

astro Contraints on light bosons

- ➡ vector boson with vacuum mass m_V 10^{-1} eV<m_V<10 MeV, eg coupled to B–L
- ➡ Strongest Constraint at light end from energy loss in red giants: $g<10^{-13}$ *Grifols, Masso, Peris*
- ➡ Also supernova constraints, fixed target
- ➡ What if it is a chameleon in dense matter?
  - ➡ density in stellar core ~ 2×10^5 gm/cm^3
- ➡ $m_V \approx g(\rho/\varepsilon)^{1/3}$ inside or near stars, detectors, could be heavy enough to evade constraints

Evading Constraints on vector boson (if couple to B, L) continued

- at high charge density $m_V \sim \rho^{1/3}$
  - for red giant: $(\rho_{core}/\rho_{earth})^{1/3} \sim 50$
  - allows new gauge boson on earth to be as much as 50 times lighter than stellar evolution bound for given coupling
  - 50000 times lighter than SN bound
  - boson in space could be much lighter than on earth (or massless)

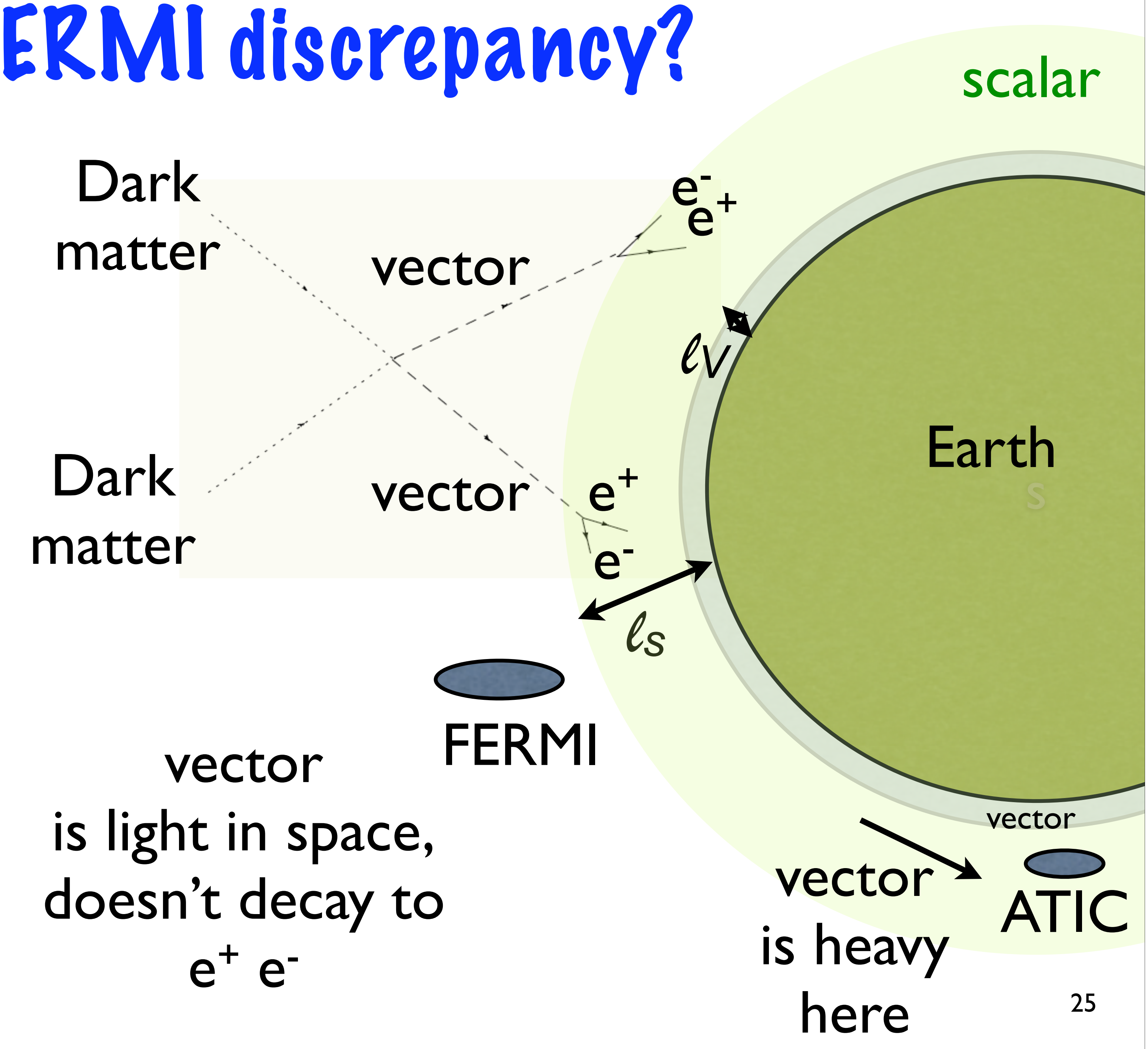
Landscape of exotic possibilities for particle physics generically includes environment dependence of mass and coupling strength of new particles

“The study of non-linear physics is like the study of non-elephant biology.”

Reynolds

Backup slides

ATIC/FERMI discrepancy?



vector is light in space, doesn't decay to $e^+ e^-$

vector is heavy here