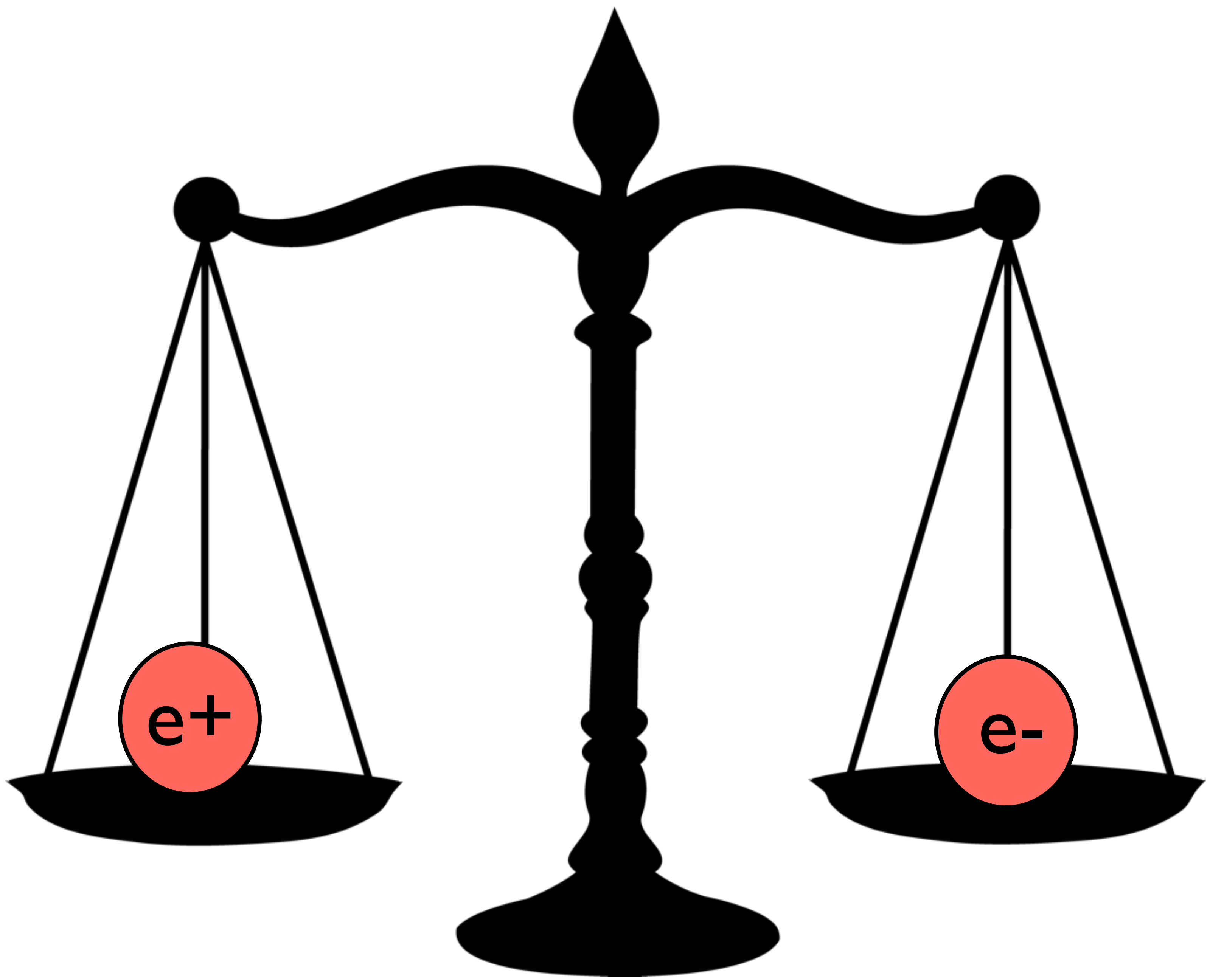
Experimental constraints on the free fall acceleration of antimatter



Martin Jankowiak Universität Heidelberg

WAG 2013 at Universität Bern November 13th

based on arXiv:0907.4110 with D.S.M. Alves & P. Saraswat

Outline

- Introduction
- Experimental input
- Atoms have many parts
- A fifth force (canceled by a sixth force)
- Conclusion

Introduction

- how large of an effect could an experiment like AGE or AEGIS possibly measure??
- if we make no theory assumptions whatsoever, this kind of question is unanswerable: "**anything is possible**"
- given the absence (to my knowledge) of any particularly plausible candidate theory we will consider two general "antigravity" scenarios:
    - unspecified modification of GR
    - fifth and sixth forces mediate by scalars/vectors (Nieto/Goldman)

(Main) Experimental input

- equivalence principle constraints for test masses in the gravitational field of the earth or sun
- experimental techniques: lunar laser ranging, free torsion pendulum, and torsion balance

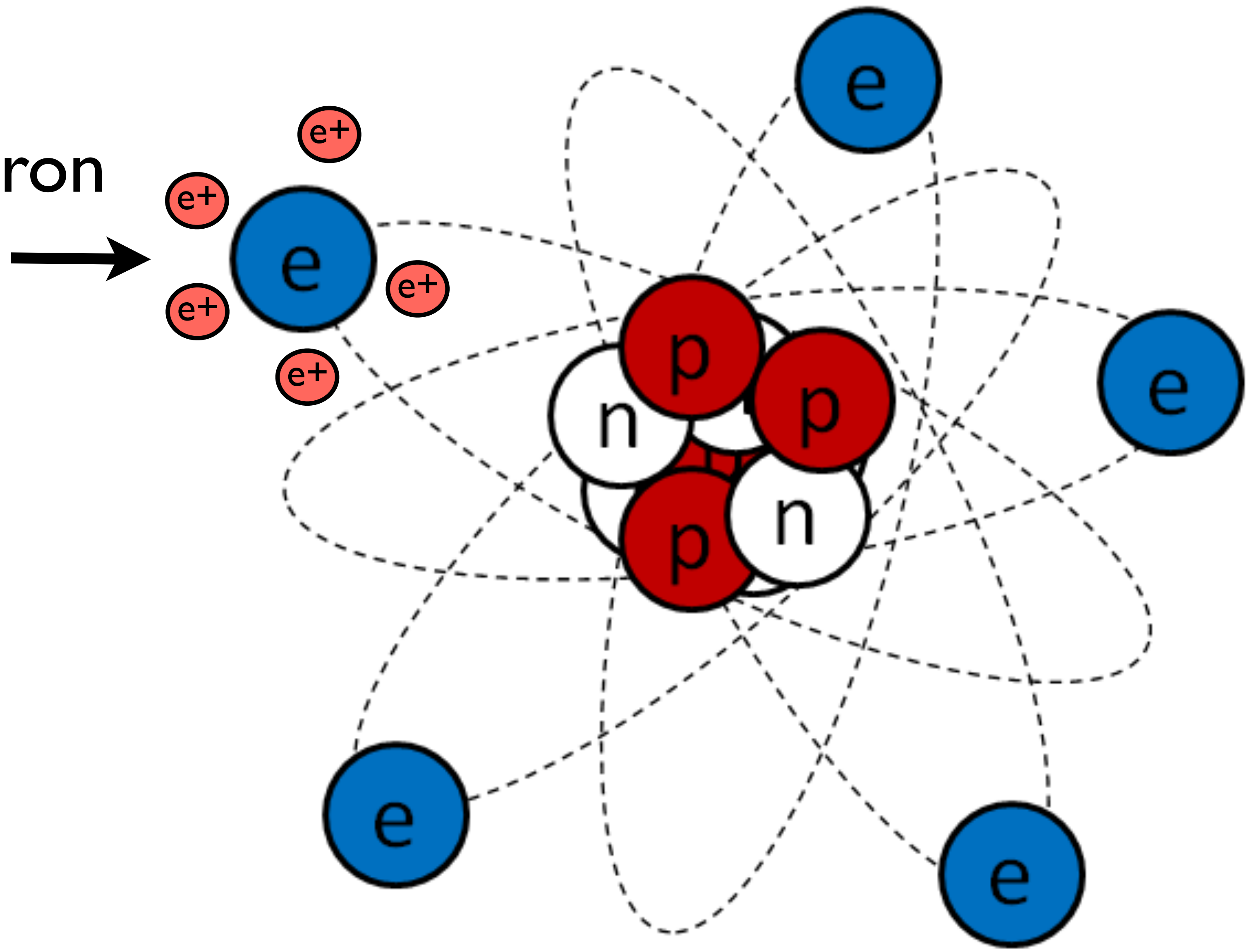
Experiment	Test bodies	Measurement
Lunar laser ranging	Earth - Moon	$\eta_{\odot,\oplus\text{-}☾} = (-1.0 \pm 1.4) \times 10^{-13}$
Braginsky and Panov	Al - Pt	$\eta_{\odot,\text{Al-Pt}} = (3 \pm 4) \times 10^{-13}$
Eöt-Wash	Be - Ti	$\eta_{\oplus,\text{Be-Ti}} = (0.3 \pm 1.8) \times 10^{-13}$
Eöt-Wash	Be - Al	$\eta_{\oplus,\text{Be-Al}} = (-1.5 \pm 1.5) \times 10^{-13}$
Eöt-Wash	Be - Cu	$\eta_{\oplus,\text{Be-Cu}} = (-1.9 \pm 2.5) \times 10^{-12}$

- up-to-date as of early 2009

Atoms have many parts

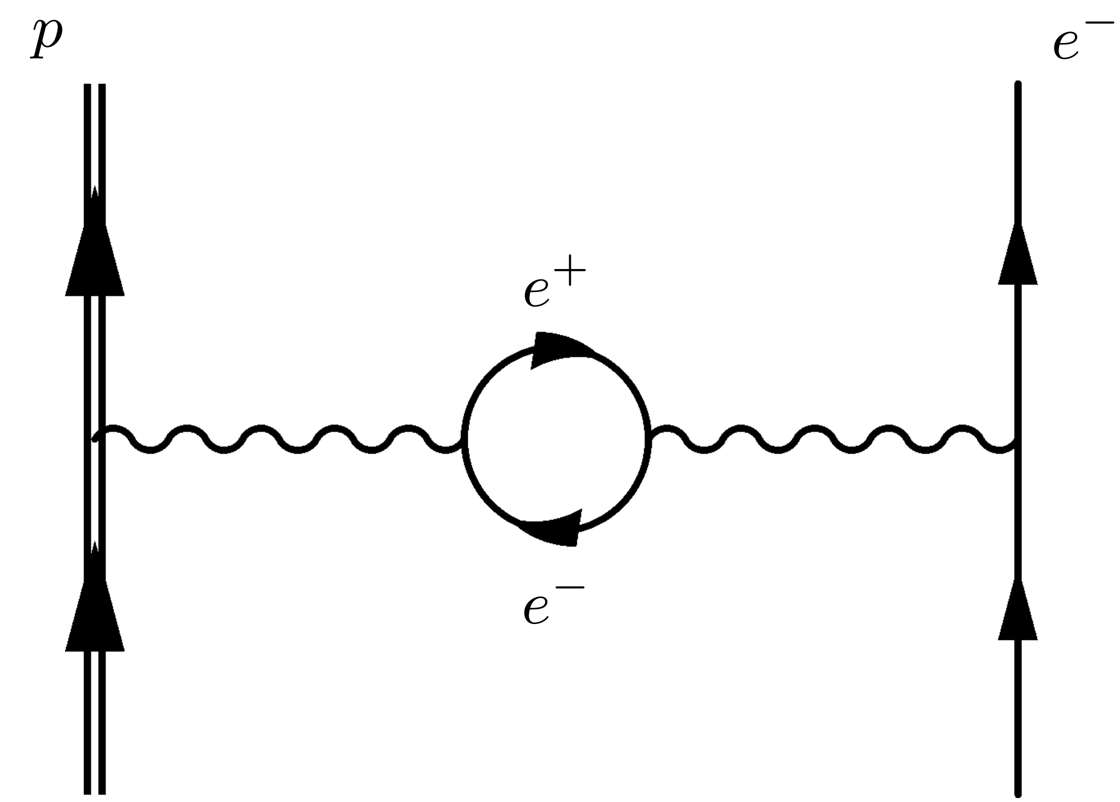
- simple idea:
  - atoms contain antimatter
  - different atoms contain different amounts of antimatter

dressed electron has positron constituents



Lamb shift

- one of the most precisely verified predictions of QED
- for simplicity focus on the vacuum polarization contribution
- electron loop contributes to the running of α at energies above the electron mass resulting in a modified Coulomb potential



- interpreted as screening of the nuclear charge by virtual electrons and positrons
- this constitutes only a small fraction of the total Lamb shift

Lamb shift

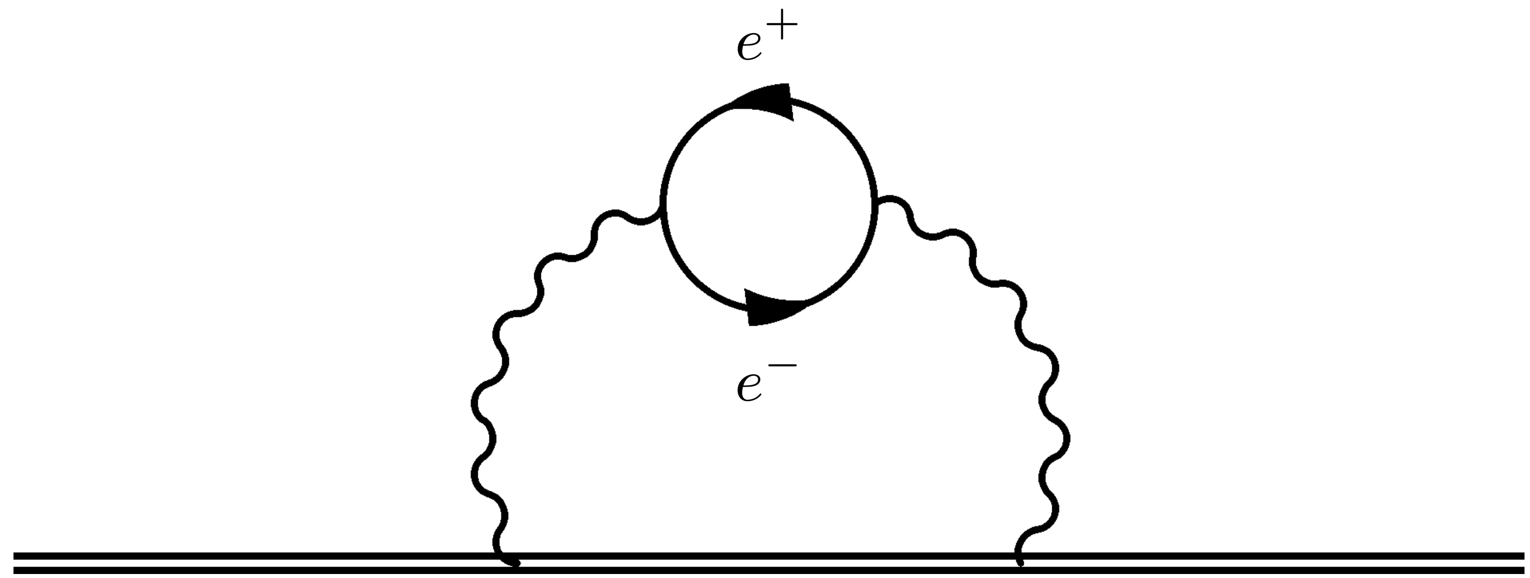
$$E_{\text{Lamb}}^{l=0} = -\frac{\alpha(Z\alpha)^4}{\pi n^3} F(Z\alpha)\, m_e$$

- here F(x) varies slowly from about 0.25 to 1.0 as Z goes from 1 to 100
- total Lamb shift has been measured up to Z=92, confirming QED predictions in the strong-field regime
- for beryllium the Lamb shift is a fraction $\sim 4 \times 10^{-14}$ of the total mass, while for titanium it is $\sim 9 \times 10^{-12}$

$$|\eta_{\oplus,\text{Be-Ti}}| = \Delta\left(\frac{E_{\text{Lamb}}}{m_{\text{atom}}}\right)\frac{|g - g_{\text{Lamb}}|}{g} \lesssim 10^{-13}$$

$$\Rightarrow \frac{|g - g_{\text{Lamb}}|}{g} \lesssim 10^{-2} \quad \Rightarrow |g_{\text{H}} - g_{\overline{\text{H}}}|/g_{\text{H}} \lesssim \boxed{10^{-2}}$$

Electrostatic self-energy of the nucleus



$$E_{\mathrm{EM}} \simeq -\frac{3}{5}\frac{\alpha Z(Z-1)}{A^{1/3}R_0} \approx \frac{0.72 Z(Z-1)}{A^{1/3}}\,(\mathrm{MeV})$$

$$\frac{E_{\mathrm{Loop}}}{E_{\mathrm{EM}}} \simeq \frac{\alpha}{4\pi}\log(m_{\mathrm{e}}^2 R_{\mathrm{nuc}}^2) \approx 10^{-3}$$

$$\Rightarrow \frac{|g - g_{\mathrm{Loop}}|}{g} \lesssim \boxed{10^{-7}}$$

- this is just the QED contribution; (potentially larger) quark loops as well

Antiquarks in nucleons

- DIS experiments have established that the proton and neutron include the antiquarks $\bar{u},\ \bar{d},\ \bar{s}$

$$F_{\bar{q}} \sim \int_0^1 x\{\overline{u}(x) + \overline{d}(x) + \overline{s}(x)\}dx \approx 0.1$$

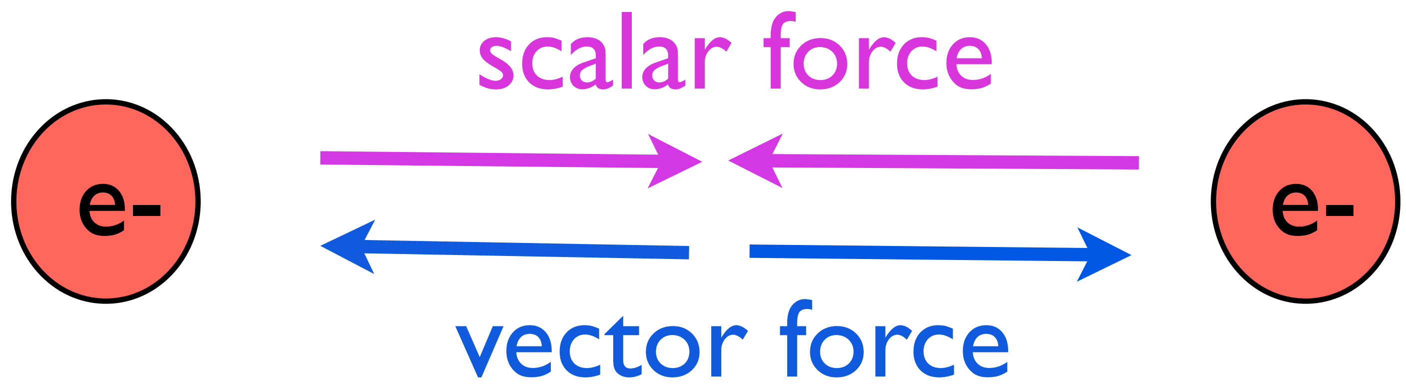
$$|\eta_{\oplus,\text{A-B}}| = F_{\overline{\mathrm{q}}}|F_{\mathrm{N}}^{\mathrm{A}} - F_{\mathrm{N}}^{\mathrm{B}}|\frac{|g - g_{\overline{\mathrm{q}}}|}{g}$$

$$|F_{\mathrm{N}}^{\mathrm{Be}} - F_{\mathrm{N}}^{\mathrm{Ti}}| \sim 10^{-3} \ \Rightarrow |g - g_{\overline{\mathrm{q}}}|/g \lesssim \boxed{10^{-9}}$$

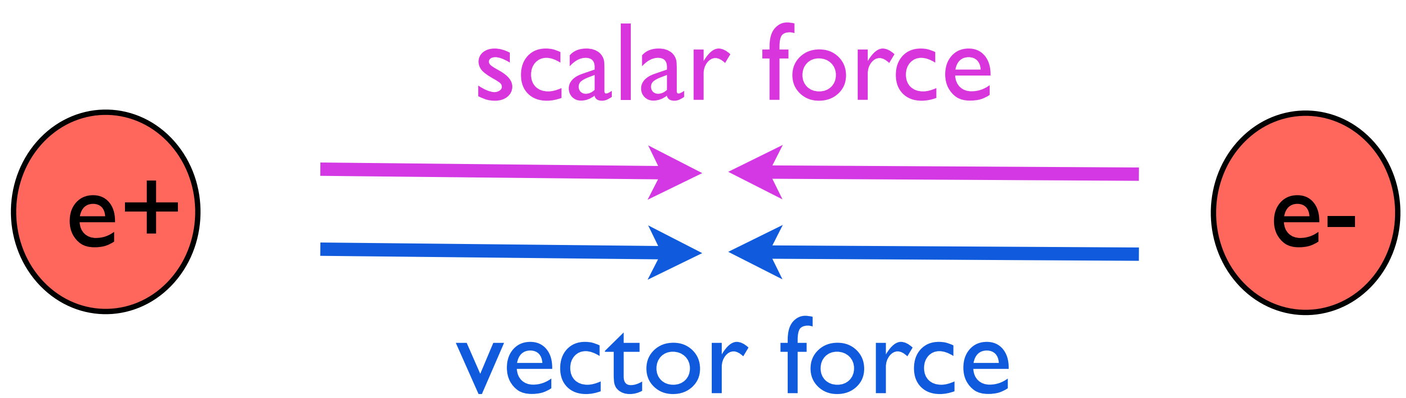
A fifth force (canceled by a sixth force)

- let's explore the scenario that there exist long-range forces of (sub)gravitational strength mediated by scalar and vector particles diabolically arranged such that they have thus far evaded detection in EP experiments but would potentially result in large deviations from g in matter-antimatter experiments
- since scalar forces are universally attractive and vector forces are attractive between unlike charges but repulsive between like charges, this scenario is a priori plausible
- but to what level can the cancellation be arranged to hold??

A fifth force (canceled by a sixth force)



arranged to approximately cancel



manifestly do not cancel

Radiative damping of binary pulsar systems

- no matter what level of cancellation is arranged, long-range forces mean light quanta that can be radiated off
- this can lead to observable differences in the orbital decay of binary pulsar systems (whose dynamics are otherwise well described by GR)
- we will consider two specific cases:
  - the vector couples to baryon number B
  - the vector couples to lepton number L

D. Krause, H. T. Kloor and E. Fischbach, "Multipole radiation from massive fields: Application to binary pulsar systems," Phys. Rev. D **49** (1994) 6892.

Baryon number coupling

- in this case we can consider dipole radiation

$$\frac{\langle \dot{E}_{\rm V} \rangle}{\langle \dot{E}_{\rm GR} \rangle} = \chi(m_{\rm V}, \epsilon) \frac{\alpha_{\rm V}}{\alpha_{\rm GR}} \left[\Delta \left(\frac{B}{\mu} \right) \right]^2 \frac{1}{a^2 \omega^2}$$

$$\alpha_{\rm V} \equiv g_{\rm V}^2/4\pi \qquad \alpha_{\rm GR} \equiv G m_{\rm H}^2 \qquad \omega = 2\pi/P_b$$

μ is the mass of the star in units of $\mathrm{m_H}$

$\chi(m_V, \epsilon)$ is a geometric factor

a is the semimajor axis

$$\frac{\langle \dot{E}_{\rm S} \rangle}{\langle \dot{E}_{\rm GR} \rangle} = \frac{1}{2} \chi'(m_{\rm S}, \epsilon) \frac{\alpha_{\rm S}}{\alpha_{\rm GR}} \left[\Delta \left(\frac{B}{\mu} \right) \right]^2 \frac{1}{a^2 \omega^2}$$

Baryon number coupling

Observed and inferred orbital parameters of J1141-6545

$(B/\mu \approx 1.1)$ neutron star with a white dwarf companion $B/\mu \approx 1$

Parameter	**Measured value**
Orbital Period P_b	0.1976509593(1) days
Eccentricity ϵ	.171884(2)
Advance of Periastron $\dot{\omega}_{\rm GR}$	5.3096(4) deg yr^{-1}
Observed Period Derivative $\dot{P}_b^{\rm obs}$	$-0.403(25) \times 10^{-12}$
Intrinsic Period Derivative $\dot{P}_b^{\rm intrinsic}$	$-.401(25) \times 10^{-12}$
Ratio of $\dot{P}_b^{\rm intrinsic}$ to GR prediction	1.04(6)

$$\frac{\alpha_{\rm SV}}{\alpha_{\rm GR}} \leq \frac{16}{15\pi} f(\epsilon)\dot{\omega}_{\rm GR} P_b \left(1 - \frac{\dot{P}_b^{\rm GR}}{\dot{P}_b^{\rm intrinsic}}\right) \left[\Delta\left(\frac{B}{\mu}\right)\right]^{-2}$$

$$|g_{\rm H} - g_{\bar{\rm H}}|/g_{\rm H} \lesssim \boxed{10^{-4}}$$

Lepton number coupling

- since neutron stars are lepton poor and white dwarfs are lepton rich $L/\mu \approx 0.5$ here we can an even stronger limit

$$|g_{\mathrm{H}} - g_{\bar{\mathrm{H}}}|/g_{\mathrm{H}} \lesssim \boxed{10^{-5}}$$

Radiative damping of binary pulsar systems

$$P_b \quad \approx \quad 10^{12}\mathrm{m} \quad \approx \quad 10^5 R_\oplus$$

- these bounds are robust and can only be evaded (while still allowing for an earth-sourced signal) by requiring the range of the mediators to lie in the range

$$R_\oplus \lesssim \lambda \lesssim 10^5 R_\oplus$$

$$10^{-19}\ \mathrm{eV} \lesssim m \lesssim 10^{-13}\ \mathrm{eV}$$

Scalar charges are not vector charges

- let the scalar couple to $T^{\mu}_{\ \mu}$
- and the vector couple to B
- adjusted to approximately cancel
- and have the same range $\lambda \gtrsim R_{\oplus}$
- approximate cancellation is possible since $B/\mu \approx 1$
- variation across periodic table is $\Delta(B/\mu) \approx \mathcal{O}(10^{-3} - 10^{-4})$

$$|\eta| = \Delta\left(\frac{B}{\mu}\right)\frac{|g_{\mathrm{H}} - g_{\overline{\mathrm{H}}}|}{2g_{\mathrm{H}}} \quad \Rightarrow \quad |g_{\mathrm{H}} - g_{\overline{\mathrm{H}}}|/g_{\mathrm{H}} \lesssim \boxed{10^{-8}}$$

Scalar charges are not vector charges

- let the scalar couple to $T^{\mu}_{\ \mu}$
- and the vector couple to L
- adjusted to approximately cancel
- and have the same range $\lambda \gtrsim R_{\oplus}$

$$|g_{\mathrm{H}} - g_{\overline{\mathrm{H}}}|/g_{\mathrm{H}} \lesssim \boxed{10^{-10}}$$

- OK but maybe we can add terms to fix things?

$$\phi \, \mathrm{Tr} \, F^2_{QCD}$$

Velocity dependence of forces

- the strength of the force mediated by vector bosons is larger than the force mediated by scalar bosons by a velocity-dependent factor $u_1 \cdot u_2$

- thus any cancellation arranged in the static limit will be undone once there is relative motion

- let’s consider the motions of nucleons within nuclei as well as the motion of atomic electrons

Velocity dependence of forces

model the nucleus as a Fermi gas:

$$\langle E_{\text{kin}} \rangle = (31\ \text{MeV}) \frac{Z^{5/3} + N^{5/3}}{(Z+N)^{5/3}}$$

thus nucleon velocities can be estimated as

$$\langle \gamma - 1 \rangle = \langle \frac{1}{2} v^2 \rangle = (3 \times 10^{-2}) \frac{Z^{5/3} + N^{5/3}}{(Z+N)^{5/3}}$$

varies at a level of 10^{-3} between different nuclei

Velocity dependence of forces

in the baryon number case this yields the bound

$$|g_{\mathrm{H}} - g_{\overline{\mathrm{H}}}|/g_{\mathrm{H}} \lesssim \boxed{10^{-7}}$$

in the lepton number case this yields the bound

$$|g_{\mathrm{H}} - g_{\overline{\mathrm{H}}}|/g_{\mathrm{H}} \lesssim \boxed{10^{-9}}$$

stronger because electron velocities vary more between nuclei

Velocity dependence of forces

these considerations are just one of the many effects that contribute to the effective scalar and vector charges of atoms.

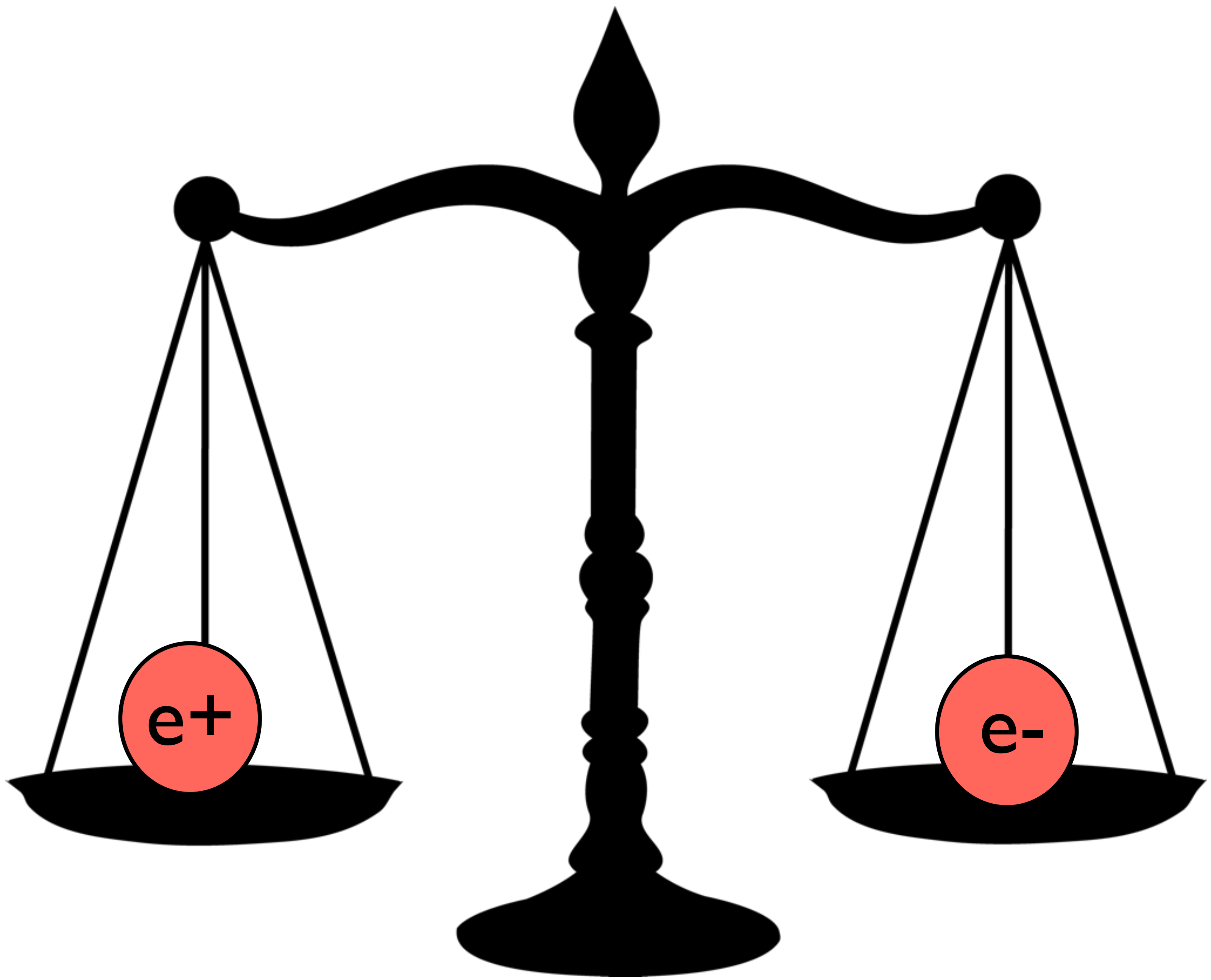
the general implication is that even if cancellation can be achieved at the level of electrons, protons, and neutrons, that cancellation would necessarily be undone at some level as one descends to the (relevant) effect field theory in which atoms are the degrees of freedom

composition dependence is generic in the scalar-vector scenario

Conclusion

Scenario	Argument	Bound on $\|g_{\mathrm{H}} - g_{\overline{\mathrm{H}}}\|/g_{\mathrm{H}}$
Modification of GR	Lamb shift	$\lesssim 10^{-2}$
	Electrostatic self-energies of nuclei	$\lesssim 10^{-7}$
	Antiquarks in nucleons	$\lesssim 10^{-9}$
Scalar-vector	Radiative damping of binary systems	$\lesssim 10^{-4}$
	Scalar charges are not vector charges	$\lesssim 10^{-8}$
	Velocity dependence	$\lesssim 10^{-7}$

if our theory assumptions are valid, then it seems that terrestrial matter-antimatter experiments should not expect to see “antigravity” at a level larger than $\sim 10^{-7}$



thank you!