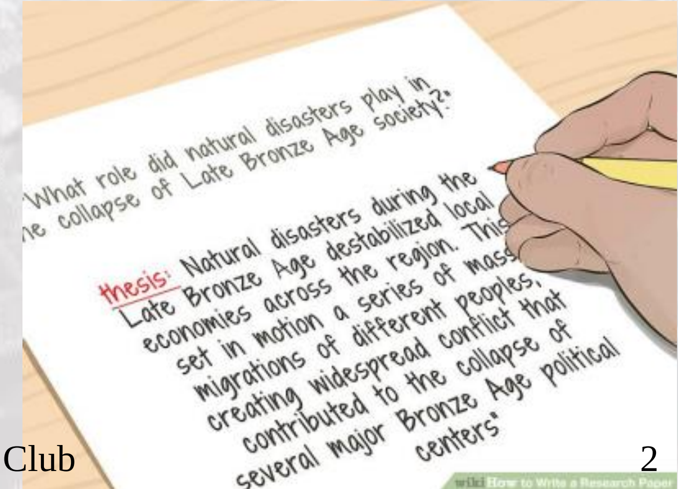
Quantum Nonfluctuations

A story whose time has passed

Papers

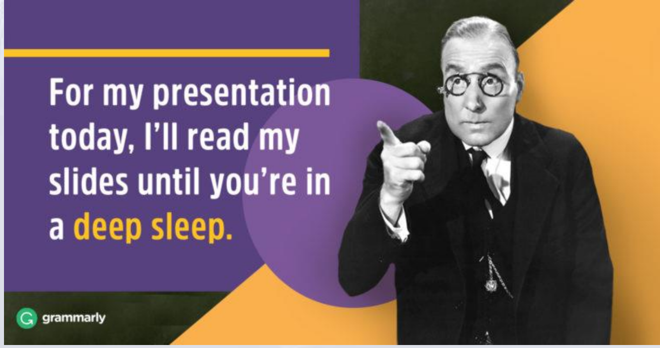
- [Nikolic 2016] Hrvoje Nikolic, “Proof that Casimir force does not originate from vacuum energy,” Physics Letters B, Elsevier, 2016-08-18 p197.
- [Jaffe 2005] R. L. Jaffe, “Casimir effect and the quantum vacuum,” Phys. Rev. D 72, 021301(R) 12 July 2005.
- [Gründler 2013] Gerold Gründler, “The Casimir-Effect: No Manifestation of Zero-Point Energy,” arXiv:1303.3790v5 [physics.gen-ph], 2013.
- Assorted others as we go on
  Lamb shift, photon interactions,
  and other vacuum (non)effects
- A bunch of my own work,
  that I hope to publish soon



One sentences

- "Certainly there is no experimental evidence for the reality of zero-point energies in quantum field theory (without gravity). ... no known phenomenon, including the Casimir effect, demonstrates that zero-point energies are real." [Jaffe 2005]
- "In total, no experimental evidence at all is indicating the measurable, observable existence of the zero-point energy of elementary quantum fields." [Gründler 2013]

What, Why, and How?



- Again: we're still doing Quantum Mechanics like its the 1930s
  - Many offhand remarks claim experimental verification of EM "vacuum energy" or "vacuum fluctuations"
  - Details are non-existent
- A lot of credible people have made such claims
  - It seems mostly just repeating what other credible people have said before them
- These claims started *before* QFT was well understood
  - Especially the electromagnetic transition from quantum to classical, discovered by Glauber in *1962* !

Why are Dirac particles called Fermions?

Outline

- Definitions, Statement of the Issue
- Till the soil, dig up our roots
- Simple proof that *electromagnetic* ZPE is unobservable
- The search for quantum theory
- Spontaneous emission
- Lamb shift
  - Heat engines
- Casimir force
- Cosmological constant

“Knowledge is good”

Statement of the Issue

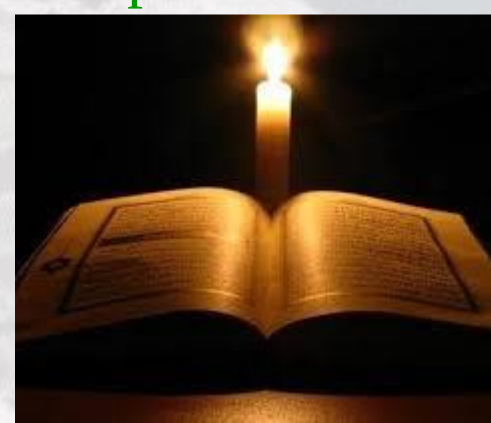
Alleged dynamic vacuum

Actual vacuum (Motel 6)

- In all such discussions, we must carefully define terms:
  - Here, I define “Quantum fluctuations” as dynamic variations changing in time
  - *I do not* mean the following things that *are* observable:
    - Thermal fluctuations
    - Sampling a random variable (aka superpositions, uncertainty), e.g., CMB temperature variations
    - Dark energy (cosmological constant)
    - Matter SHO ground state energy
- Caveat: I have not studied more esoteric things such as Higgs-sector physics
  - I’m told there’s more going on in the Higgs-sector
  - I’ll believe it when I see it (fool me twice ...)

No physics superheroes

- It is no besmirchment to quantum pioneers to note that sometimes they were wrong
  - Many famous quotes have the physics wrong
    - Deification has hobbled physicists for years, or even decades
  - We know better now
- Inspiration vs. Theory
  - Inspiration is the motivation behind the development
  - But the *theory* is what it predicts
    - Regardless of its relationship to the inspiration



Hamiltonian and the origin of ZPE

- QED is a hamiltonian theory
- No hamiltonian, no theory
  - Know hamiltonian, know theory
  - The search for the theory *is* the search for the hamiltonian
- Canonical quantization of the EM field
  - Starts by *assuming* the field is like a harmonic oscillator, and then uses *analogy* with a particle SHO, and *classical* electromagnetic formulas, to *suggest* a form for the quantized field:

$$\hat{H}_{em} \propto \hat{E}^2 \propto \hat{a}^\dagger \hat{a} + \frac{1}{2}$$

Alexander Hamilton
in his early years.

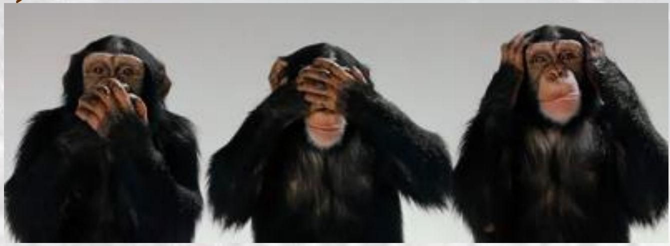
William Rowan Hamilton
in his later years.

Simple proof that EM ZPE is unobservable

- The "canonical" hamiltonian is: $\hat{H}_{em} \propto \hat{a}^{\dagger}\hat{a} + \frac{1}{2}$
  - "Derived" from the square of the electric field operator
- An additive constant in the hamiltonian has no effect on the dynamics (i.e. equations of motion)

$$\dot{q} = \frac{\partial H}{\partial p}, \qquad \dot{p} = -\frac{\partial H}{\partial q}$$

$$\frac{d\hat{\mathcal{O}}}{dt} = \frac{i}{\hbar}\left[\hat{H}, \hat{\mathcal{O}}\right] + \frac{\partial \hat{\mathcal{O}}}{\partial t}$$



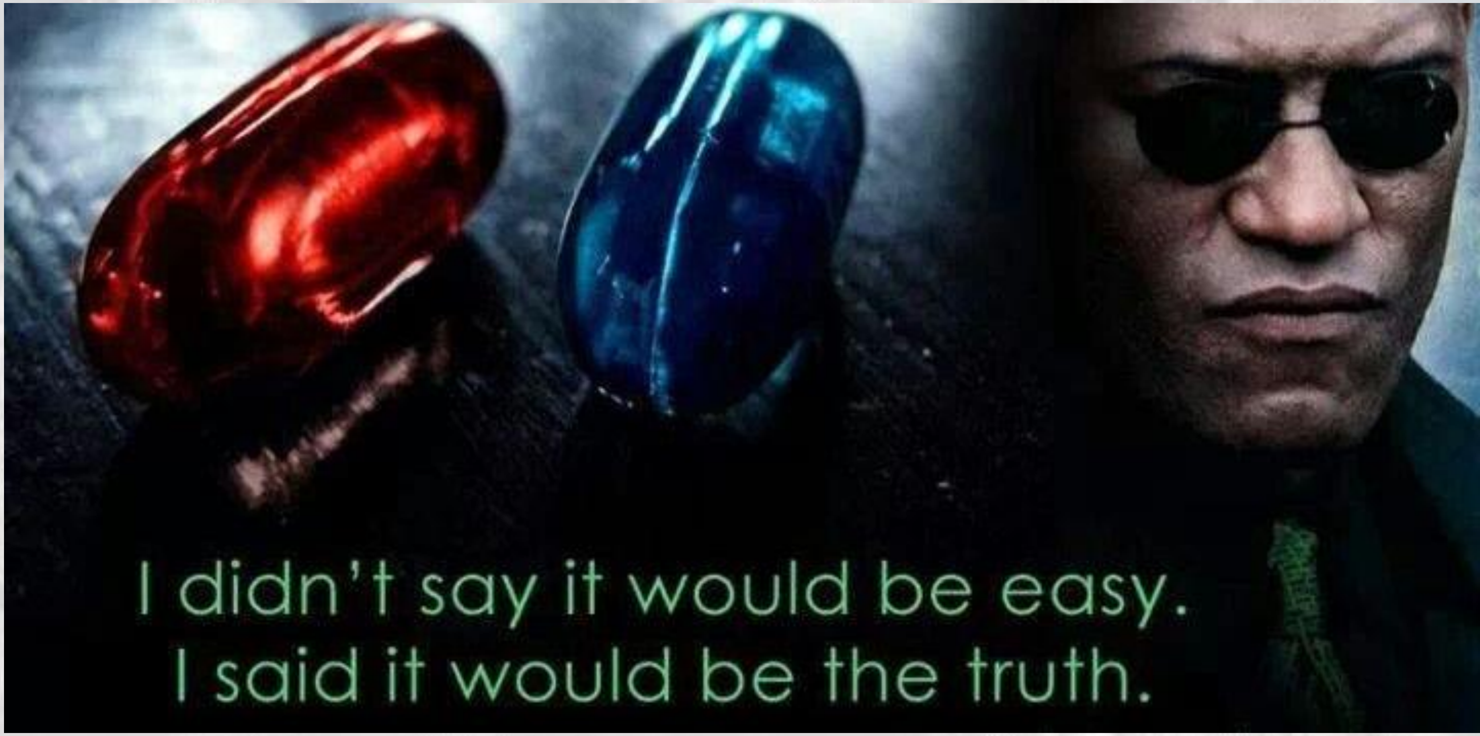
  - Hence the ZPE cannot ever be observed
- The constant of ½ is neither a source nor a sink of energy
  - It cannot interact with anything
- Scientifically, if it cannot be observed in principle, then it does not exist

Making wise choices

- There is no more reason to believe the vacuum is filled with infinite EM energy density, than there is to believe it is filled with infinite "negative energy" electrons
- Zero point energy or fluctuations are no more a part of QED than the luminiferous ether is a part of electromagnetics
- We *choose* the simplest hamiltonian consistent with experiment: $\hat{H}_{em} \propto \hat{a}^{\dagger}\hat{a}$

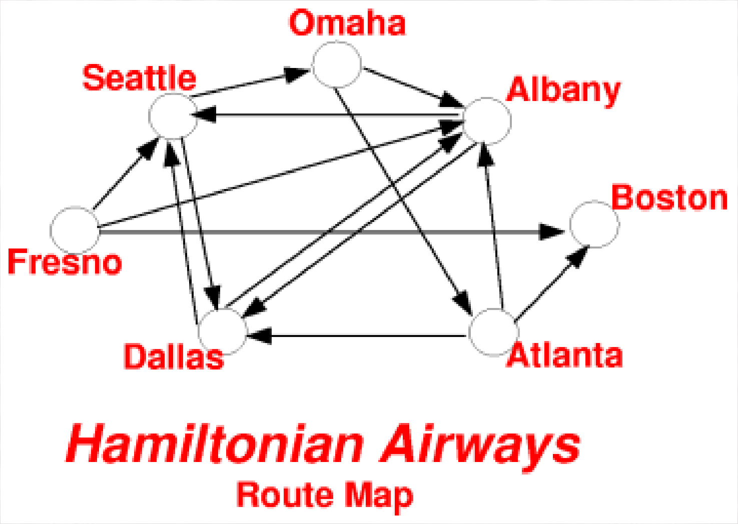
Burden of proof

- Prove there is *no* vacuum energy?
- Nay, show me some evidence that there *is*!



The search for a theory is the search for its hamiltonian

- The total energy is not always the hamiltonian (and the hamiltonian is not always the total energy)
- The defining property of the hamiltonian is that it is the generator of time evolution.



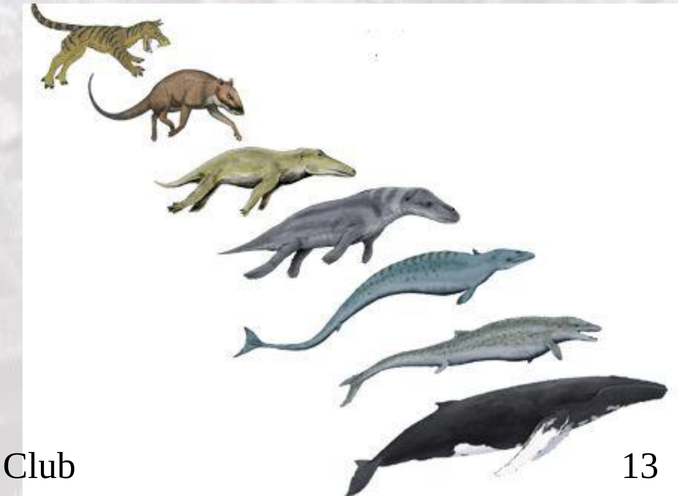
The quantum theory of evolution: a smooth operator

$$\frac{\partial}{\partial t}\left|\psi\right\rangle = \frac{-i}{\hbar}\hat{H}\left|\psi\right\rangle$$

Schrodinger equation,
generator of time evolution

- Time evolution is smooth
  - Recall my Journal Club talk from a few years ago
    - (Smooth even when taking a measurement)
  - No bubbling, boiling, roiling, frothing quantum latte of foam

Now: on to the evidence



Lack of spontaneity

- Spontaneous absorption
  - Fluctuations or not, you can’t absorb a photon you don’t have

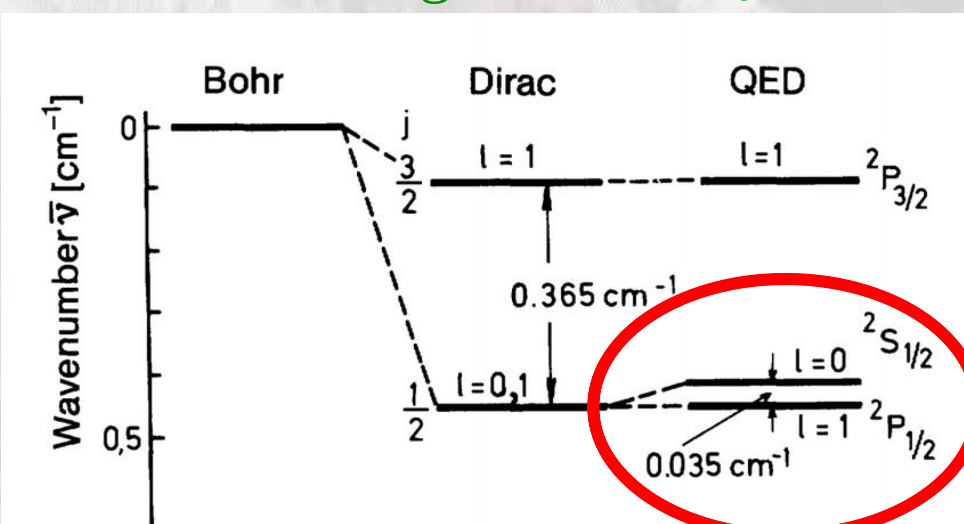
$$\text{absorption rate} \propto \langle N|\hat{a}^{\dagger}\hat{a}|N\rangle = N \quad \rightarrow \quad rate(|vac\rangle) = 0$$

- Spontaneous emission
  - Emission probability: wrong by a factor of 2

$$R_{vac} \propto \langle 0|\hat{E}^2|0\rangle = K\left(\frac{1}{2}\right); \qquad R_{QED} \propto \left|\langle 1|\hat{E}|0\rangle\right|^2 = K \quad where \quad K \equiv (\text{constant})\hbar\omega$$

Innocent Lamb

- General "Lamb shift:" a shift in electron orbital energy compared to Dirac equation
  - Mostly the upshift of the *s* orbitals
- "The" Lamb shift is the hydrogen $2s_{1/2}/2p_{1/2}$ energy difference
  - Predicted by Dirac equation to be exactly zero (same *j*)
  - Measured at ~1060 MHz
  - Strong driver of QED theory development



Lamb shift: QED

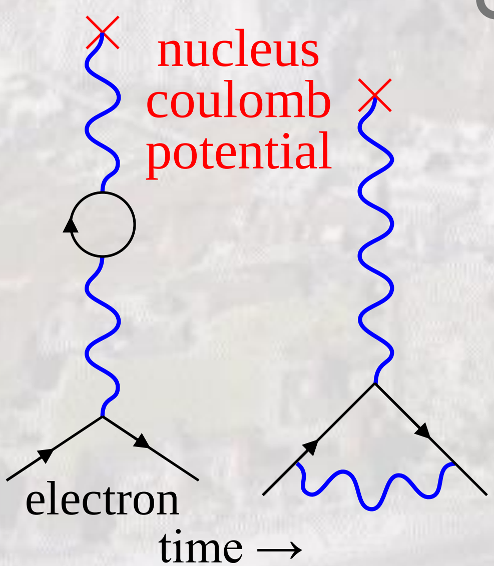
- Stationary state of full interacting hamiltonian:
  - Superposition of both no-photon and 1-photon states
    - (So-called "virtual" photons)

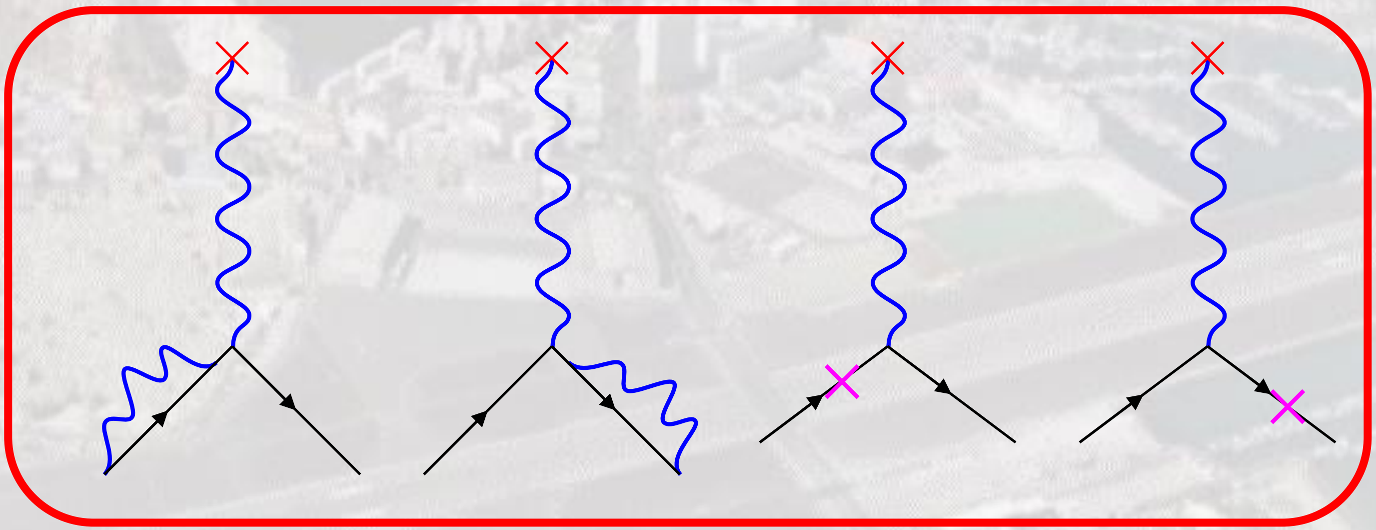
$$\left|\psi_{2s_{1/2},true}\right\rangle = c_1\left|\psi_{100}\right\rangle\left|vac\right\rangle + c_2\left|\psi_{100}\right\rangle\left|N_{k_1\lambda_1}=1\right\rangle + c_3\left|\psi_{100}\right\rangle\left|N_{k_1\lambda_2}=1\right\rangle + c_4\left|\psi_{100}\right\rangle\left|N_{k_2\lambda_1}=1\right\rangle + \ldots$$

Dirac state, no photons

Dirac state, one photon

$$+c_5\left|\psi_{200}\right\rangle\left|vac\right\rangle + c_6\left|\psi_{200}\right\rangle\left|N_{k_1\lambda_1}=1\right\rangle + \ldots$$

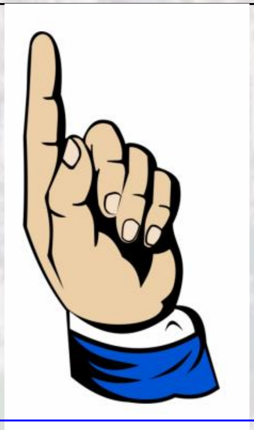




Credit where credit is due

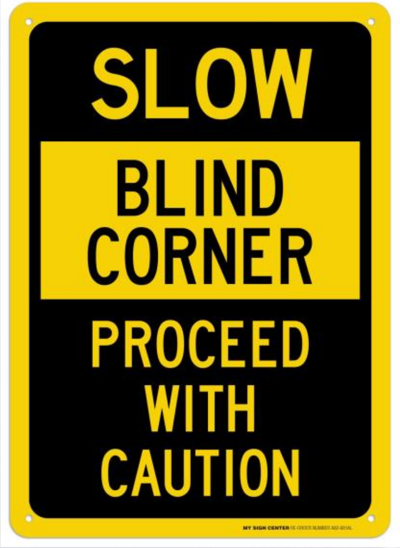
- Theodore Welton published the idea that the Lamb shift might be loosely estimated from some kind of vacuum fluctuations [1948]
  - But he noted:
    - This is “a semiquantitative calculation”
    - “we shall assume that the position fluctuation is a real concept, while we shall think of the energy of interaction ... as having no physical reality”
      - Certainly unphysical
      - The whole point is that the electron energy is raised!
    - His summary [p1167] says, “The result suffers, however, from the obvious disadvantage that a non-relativistic Hamiltonian was used ... where the non-relativistic assumption is clearly seriously in error”
- It was an idea worthy of its time [1948]
  - But not of the 21st century
- It never actually worked!
  - E.g., Spectral line shape is as predicted by QED, and does *not* include the additional variation predicted by vacuum fluctuations [Bethe+ 1957]

Theodore A. Welton
1918-2010
Undated photo, apparently just before incarceration.



Herbert Callen and Welton are also known for proving the fluctuation dissipation theorem in 1951

Lamb shift: Welton's original reasoning



- There are more caveats from Welton:
  - E.g., 3D Taylor expansion does not converge for 1/*r* potential
    - But Welton's uses the first term, anyway
      - He has some further quantum argument for this
- Both QED and fluctuations arrive at a Doubly divergent integral

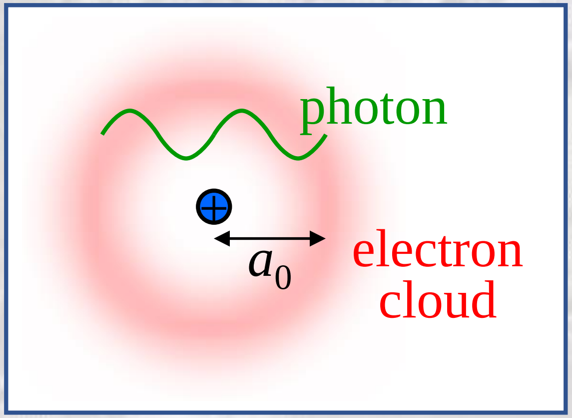
$$\Delta E \propto \int_0^\infty \frac{d\omega}{\omega} \to \ln \frac{\text{upper-cutoff}}{\text{lower-cutoff}}$$

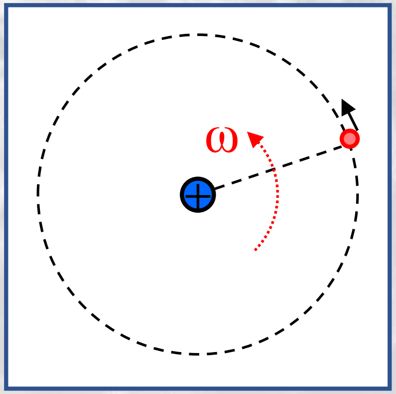
  - QED provides reliable upper and lower bounds
    - Vacuum fluctuations do not
  - The lower integration limit used is "an amazingly high value" [Bethe 1947], and "seems implausibly large" [Welton 1948]
    - Do logarithmic bounds matter?

Boundless optimism

- What lower bound to use?
- Bethe: $\Delta E \propto \ln \frac{511\,\mathrm{keV}}{242\,\mathrm{eV}} = 7.7 \;\rightarrow\; 1000\,\mathrm{MHz}$
- $\lambda \sim a_0$: $\Delta E \propto \ln \frac{511\,\mathrm{keV}}{23\,\mathrm{kev}} = 3.1 \;\rightarrow\; 400\,\mathrm{MHz}$
- $\lambda \sim$ Ry: $\Delta E \propto \ln \frac{511\,\mathrm{keV}}{13.6\,\mathrm{eV}} = 10.5 \;\rightarrow\; 1400\,\mathrm{MHz}$
- $\omega \sim$ Bohr $l = 1$: $\Delta \mathrm{E} \propto \ln \frac{511\,\mathrm{keV}}{27\,\mathrm{eV}} = 9.8 \;\rightarrow\; 1300\,\mathrm{MHz}$.

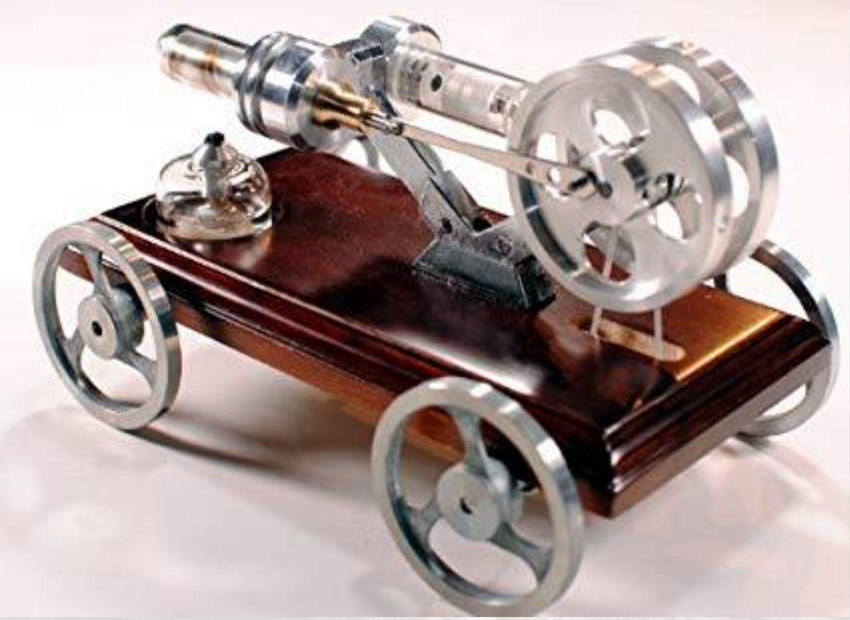
Wide range of values to claim “agreement” from





Dynamic vacuum = perpetual motion

- Dynamic random E-fields would be a source of thermal energy, and could drive a perpetual motion heat engine (dumping into, say, the 3 K CMB)
  - Unless you can "run down" the vacuum
  - Which violates the permanence of vacuum fluctuations

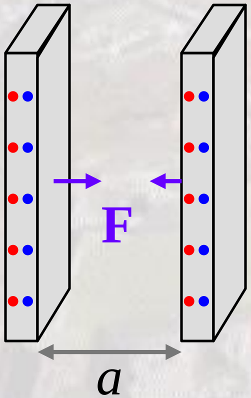


Casimir force: QED

- Van der Waals forces [Lifshitz 1955], [Schwinger+ 1978]
  - Spontaneous induced polarization

$$F = \hbar c \frac{\pi^2}{240 a^4} \qquad \textit{where} \qquad a \equiv \text{plate separation}$$

  - No e, just $\hbar$: all quantum field, no charge?
    - Makes it look purely quantum field, with no charge interaction
  - Actually, this is the limit of good conductors [Jaffe 2005]
    - $e \to \text{large}$ implies $F \to \text{constant}$

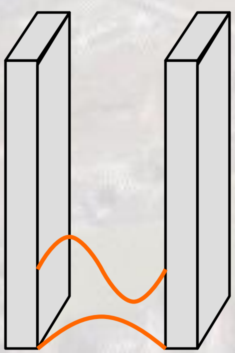


$$F(a,e,m) = -\frac{e^2}{\pi}\int_m^\infty dt\, \frac{t^2}{\sqrt{t^2 - m^2}} \cdot \frac{\exp(-2at)}{4t^2 + 4et + e^2\left(1-\exp(-2at)\right)}, \qquad \hbar = c = 1$$

where $a \equiv$ conductor spacing; $e \equiv$ electric charge; $m \equiv$ field mass, later taken to 0.

Casimir force the wrong way

- Fit waves into the space
  - Smaller space fits fewer waves ⇒ less energy, attractive force
  - No *e* (electronic charge), just $\hbar$
    - Makes it look purely quantum, with no charge interaction
  - The force below is valid for only a *tiny* slice of realistic situations
    - Sometimes, even the wrong model gives the right answer some of the time (e.g., the Bohr model)



$$F = \hbar c \frac{\pi^2}{240 a^4} \quad \textit{where} \quad a \equiv \text{plate separation}$$

Less than nothing

> "What do you mean *less* than nothing?" replied Wilbur. "I don't think there is any such thing as less than nothing. Nothing is absolutely the limit of nothingness. It's the lowest you can go. It's the end of the line. How can something be less than nothing? If there were something that was less than nothing, then nothing would not be nothing, it would be something - even though it's just a very little bit of something. But if nothing is nothing, then nothing has nothing that is less than it is."
>
> — E.B. White, Charlotte's Web

- Cancellation of the vacuum is physically impossible
  - The E^2 operator is positive definite (that means for *any* state)

$$0 = \langle \psi_{EM} | \underbrace{\left(\hat{a}^\dagger \hat{a} + \frac{1}{2} \right)}_{\propto \hat{E}^2} | \psi_{EM} \rangle = \langle \psi_{EM} | \hat{a}^\dagger \hat{a} | \psi_{EM} \rangle + \frac{1}{2} \quad \Rightarrow \quad \langle \psi_{EM} | \hat{a}^\dagger \hat{a} | \psi_{EM} \rangle = -\frac{1}{2}$$

- [Gründler 2013] demonstrates convincingly that the vacuum energy approach to the Casimir force cannot be generalized to include realistic plates having finite conductivity
  - Attempting to do so necessarily invalidates the argument
    - Because it demands interactions
  - Similarly for dielectrics
  - Or finite temperature delectrics
  - Or short distances, where $F \sim 1/a^3$
- The vacuum-fields argument is all or nothing
  - Which in this case, means it is nothing

Casimir and Alice

- Alice throws a shot-put horizontally off a cliff
  - Usual simplifications: no air, uniform gravity, etc

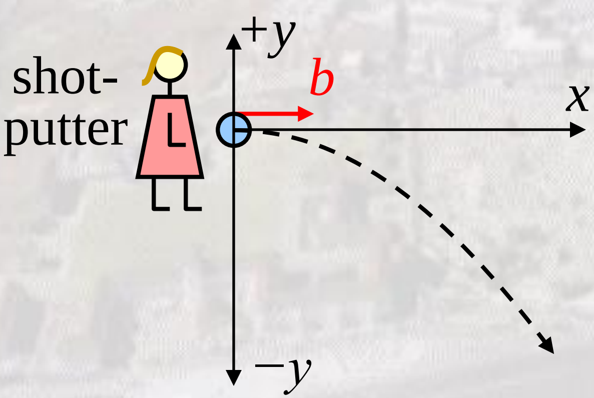
$$H = T + V = \frac{p_x^2}{2m} + \frac{p_y^2}{2m} + mgy \qquad F_x = -\frac{\partial H}{\partial x} = 0$$

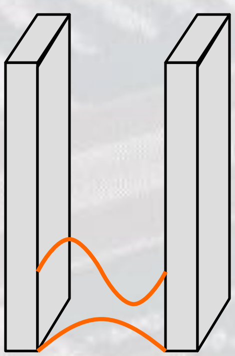
$$x(t) = bt, \qquad y(t) = -\frac{1}{2} g t^2$$

$$t = x / b \quad \Rightarrow \quad y = -\frac{g}{2}\frac{x^2}{b^2},$$

~~$$H_{alt} = \frac{p_x^2}{2m} + \frac{p_y^2}{2m} - m\frac{g^2 x^2}{2b^2}$$~~

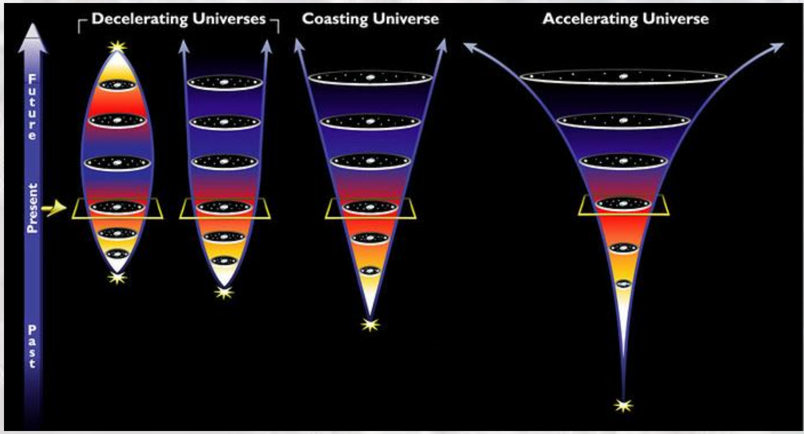
~~$$F_x = -\frac{\partial H_{alt}}{\partial x} = m\frac{g^2}{b^2}x$$~~



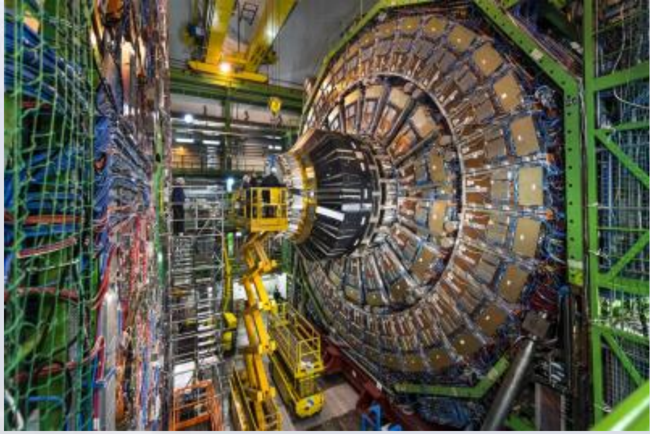


Cosmological constant

- Once again, “zero-point energy” fails
  - The EM field alone is many orders too big
- Since there is no ZPE, no fluctuations, and no reason to think there should be:
  - My conclusion: Λ is almost certainly unrelated to EM ZPE
  - It must be something else
- But I don’t know Higgs-sector physics
  - Some say there’s hope in that



Experiment and Theory



- Experimentally, there are no vacuum EM fields:
  - There is no spontaneous absorption
  - The spontaneous emission rate is wrong
  - The Lamb shift is stable (not variable)
  - Vacuum fluctuations cannot drive a heat engine.
- Theoretically:
  - Constants in the hamiltonian cannot be observed
  - Uncertainty and superpositions are not fluctuations,
  - Vacuum fluctuations cannot derive the Lamb shift
  - Feynman diagrams do not imply fluctuations
  - Vacuum fields cannot derive the Casimir force (for either ideal or realistic plates)

Prediction

- In the end, we cannot use the notion of vacuum fields to reliably estimate any phenomenon, because:
  - They are unreliable visualizations that may or may not give approximate quantitative results
  - Their validity cannot be determined without a proper QED treatment
- Instead, we must always use QED to reliably compute observable outcomes

Recap

- The common error in reasoning about the vacuum is
  - (1) starting with classical formulas,
  - (2) demanding that quantum operators follow the classical formulas, and
  - (3) insisting that the resulting unobservable constants have physical meaning.
- Instead, one should search for the QED hamiltonian that
  - (1) satisfies experiment,
  - (2) reduces to classical formulas in the appropriate limits, and
  - (3) is as simple as possible.
  - Then vacuum fields never arise.
- Not only are vacuum fields unnecessary to QED, they are precluded by QED from any observable effects.
- For vacuum fields to be real, there must be some larger theory that fully reproduces all results of QED, and additionally includes observable consequences of vacuum fields.

Observations and thoughts

- If a thousand people say a wrong thing, it is still a wrong thing.
- Almost all papers that consider ZPE in detail conclude it doesn't exist
  - Claims for its existence are usually just offhand remarks, with little justification
- There is a consistent historical pattern of making a discovery with well-established physics, ...
  - And only later looking for, and "finding," a way to describe it in vague, vacuum field terms. Vacuum fields seem to always be an afterthought, rather than a reliable physical basis.
- Maybe Higgs-physics can resuscitate the cosmological constant as vacuum-field energy