Lab Tests of Dark Energy

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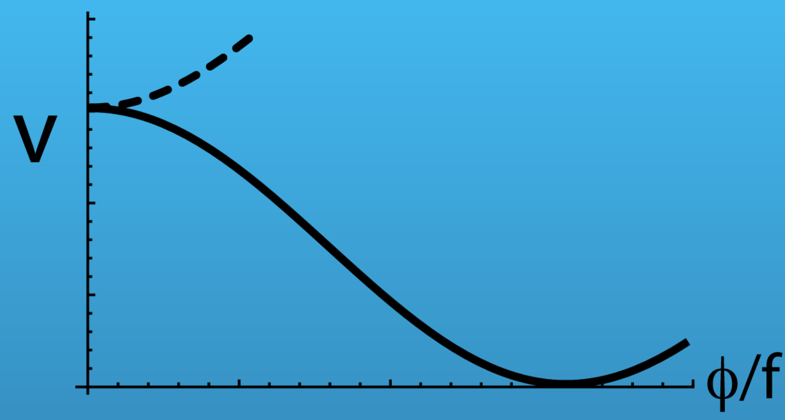
Dark Energy Accelerates the Universe

Collaboration with Mike Romalis (Princeton),
Deanne Dorak & Leo Motta (Dartmouth)

“Possible laboratory search for a quintessence field,” MR+RC, arxiv:1302.1579

Dark Energy vs. The Higgs



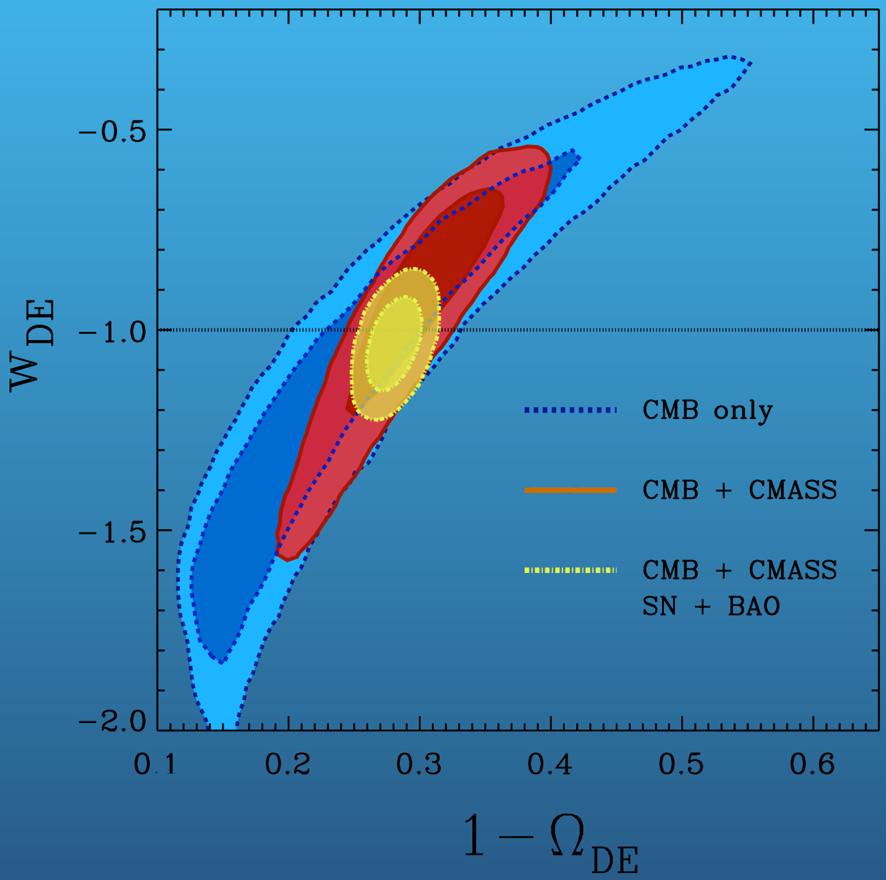
Higgs: *Let there be mass*

$$m(\phi) = g\phi$$

$$\ddot{a}/a > 0$$

Quintessence: *Accelerate It!*

Dynamical Field

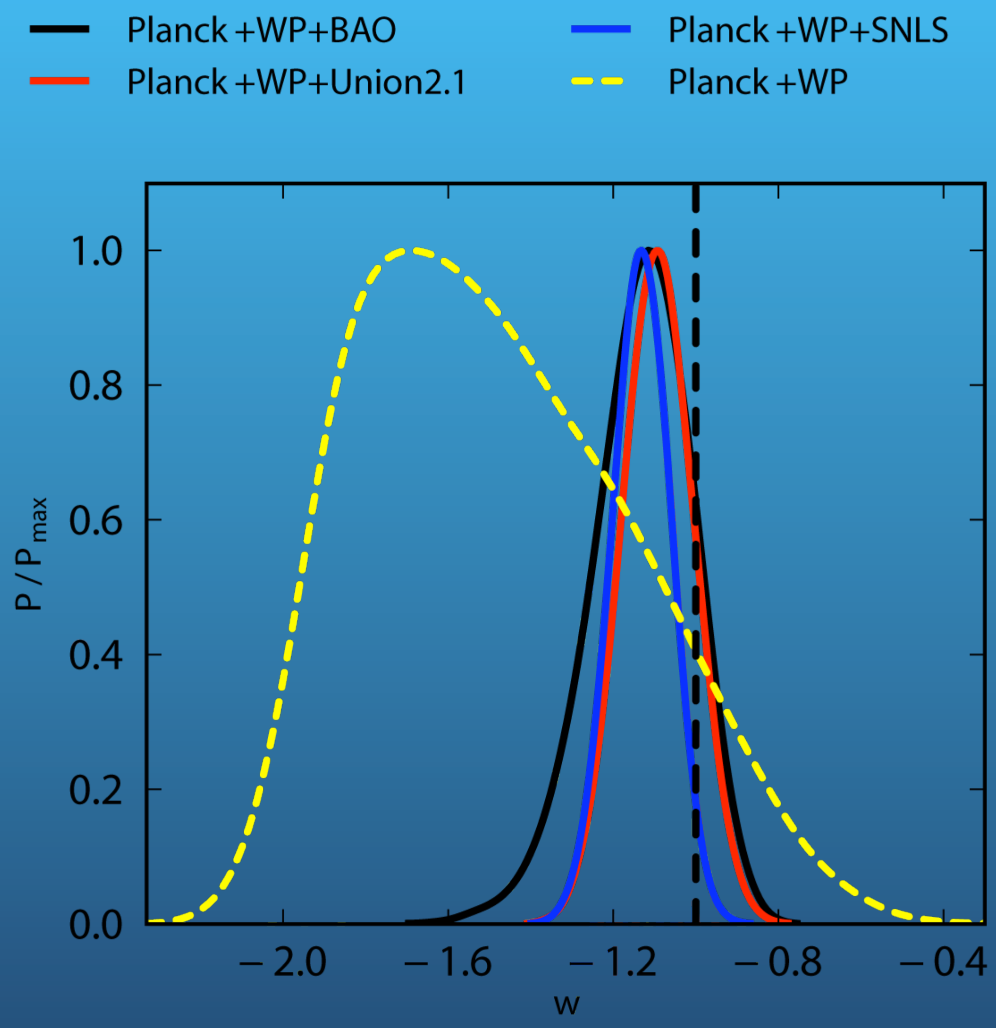


$$w_{DE} = -1.033^{+0.074}_{-0.073}$$

$$1 - \Omega_{DE} = 0.281 \pm 0.012$$

Clustering of Galaxies in SDSS-III / BOSS: Cosmological Implications, Sanchez et al 2012

Dynamical Field

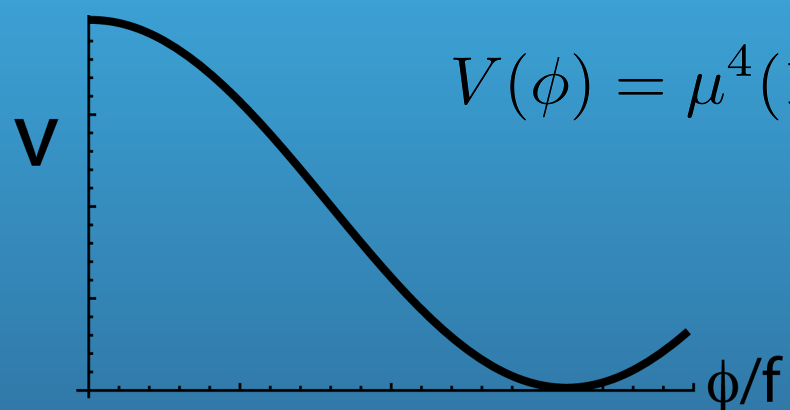


Planck 2013

Cosmological Parameters XVI

Dark Energy Cosmic Scalar Field

$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 - V(\phi) + \mathcal{L}_{sm} + \mathcal{L}_{int}$$



$$V(\phi) = \mu^4(1 + \cos(\phi/f))$$

Cosmic PNGBs, Frieman, Hill and Watkins, PRD 46, 1226 (1992)

"Quintessence and the rest of the world," Carroll, PRL 81, 3067 (1998)

Dark Energy Couplings to the Standard Model

$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 - V(\phi) + \mathcal{L}_{sm} + \mathcal{L}_{int}$$

Photon-Quintessence

$$\mathcal{L}_{int} = -\frac{\phi}{4M} F_{\mu\nu}\widetilde{F}^{\mu\nu}$$

$$= \frac{\phi}{M}\vec{E}\cdot\vec{B}$$

“dark” interaction: quintessence does not see EM radiation

Dark Energy Coupling to Electromagnetism

Varying ϕ creates an anomalous charge density or current

$$\vec{\nabla} \cdot \vec{E} - \rho/\epsilon_0 = -\frac{1}{Mc}\vec{\nabla}\phi \cdot \vec{B}$$

$$\vec{\nabla} \times \vec{B} - \mu_0\epsilon_0\frac{\partial \vec{E}}{\partial t} - \mu_0\vec{J} = \frac{1}{Mc^3}(\dot{\phi}\vec{B} + \vec{\nabla}\phi \times \vec{E})$$

Magnetized bodies create an anomalous electric field
Charged bodies create an anomalous magnetic field
EM waves see novel permittivity / permeability

Dark Energy Coupling to Electromagnetism

Cosmic Solution:

$$\dot{\phi}/Mc^2 \sim H$$

$$\nabla\phi/Mc^2 \sim Hv/c^2$$

$$\hbar H \sim 10^{-42}\mathrm{GeV}$$

- **source terms are very weak**
- **must be clever to see effect**

Dark Energy Coupling to Electromagnetism

Cosmic Birefringence:

wave equation $$\mu_0\epsilon_0\frac{\partial^2}{\partial t^2}\vec{B} - \nabla^2\vec{B} = \frac{\dot{\phi}}{Mc}\vec{\nabla}\times\vec{B}$$

dispersion $$\omega^2/c^2 - k_{L,R}^2 = \pm\frac{\dot{\phi}}{Mc}k_{L,R}$$

birefringence $$\Delta\theta = \frac{1}{2Mc^2}\int\dot{\phi}\,dt = \frac{\Delta\phi}{2Mc^2}$$

Dark Energy Coupling to Electromagnetism

Cosmic Birefringence:

CMB polarization rotates propto evolution of quintessence

$$\Delta\theta = \Delta\phi / 2Mc^2$$

Absence of CMB B-modes as upper bound on rotation of E-modes

$$-1.41^\circ < \Delta\theta < 0.91^\circ \ (95\%\mathrm{CL})$$

Komatsu et al (WMAP7), ApJS 192, 18 (2011)

Dark Energy Coupling to Electromagnetism

Anisotropic Cosmic Birefringence:

Rotation varies across sky due to quintessence fluctuations

$$\Delta\theta(\hat{n}) = \Delta\phi(\hat{n})/2Mc^2$$

Model of fluctuations, correlation with T, forecasts
RC, Gluscevic, Kamionkowski, PRD 84, 043504 (2011)

First CMB constraints on direction-dependent birefringence
Gluscevic et al, PRD 86, 103529 (2012)

Also: Yadav et al, PRD 79 123009 (2009), PRD 86 083002 (2012)

Dark Energy Coupling to Electromagnetism

In a weak gravitational field:

$$\Box\phi = V' \qquad \phi \rightarrow \phi_0 + \delta\phi$$

$$\left(\frac{d^2}{dr^2} + \frac{2}{r}\frac{d}{dr}\right)\delta\phi = V_0''\delta\phi + 2UV_0'$$

$$\vec{g} = -\vec{\nabla}U$$

local gradient $$\vec{\nabla}\delta\phi = 2(V_0'/V_0'')\vec{g}/c^2$$

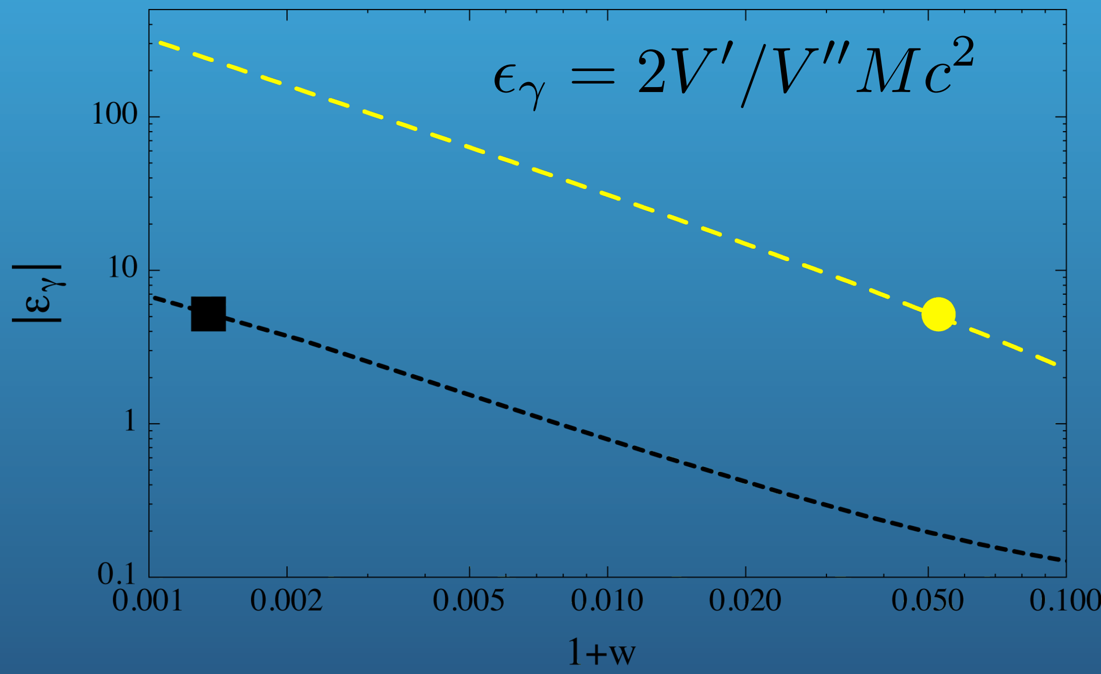
$$\epsilon_\gamma = 2V'/V''Mc^2$$

Dark Energy Coupling to Electromagnetism

Local solution: $\nabla \delta\phi / M c^2 \sim \epsilon_\gamma g / c^2$

$\hbar \epsilon_\gamma g / c^2 \sim 10^{-32} \mathrm{GeV}$

$\epsilon_\gamma = 2V' / V'' M c^2$

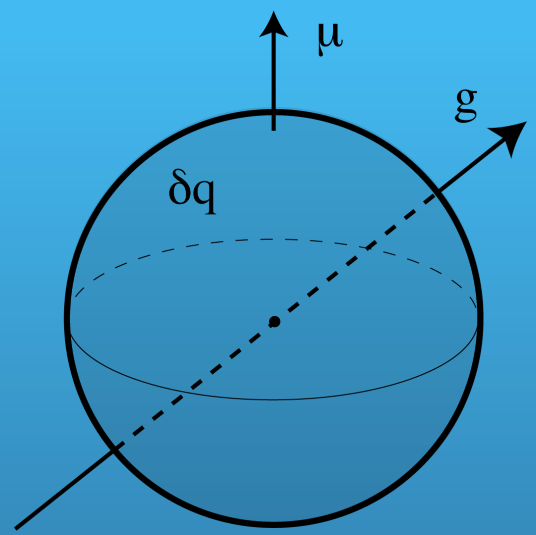


Dark Energy Coupling to Electromagnetism

$$\vec{\nabla}\cdot\vec{E} - \rho/\epsilon_0 = -\frac{\epsilon_\gamma}{c}\vec{g}\cdot\vec{B}$$

$$\vec{\nabla}\times\vec{B} - \mu_0\epsilon_0\frac{\partial\vec{E}}{\partial t} - \mu_0\vec{J} = \frac{\epsilon_\gamma}{c^2}\vec{g}\times\vec{E}$$

Lab Tests



$$\vec{B} = \frac{2}{3}\mu_0 \vec{M}$$

neutron as magnetized sphere

charge due to the local field

$$\delta q = \frac{2\epsilon_\gamma}{3c^3}\vec{g}\cdot\vec{\mu}$$

$$\simeq 10^{-32} e$$

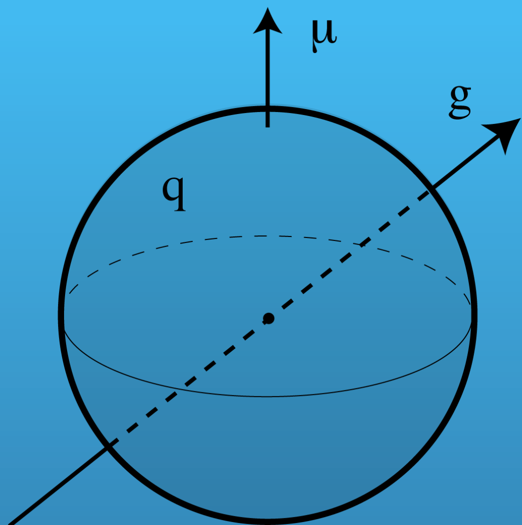
$$q_N = -0.4(\pm 1.1) \times 10^{-21} e$$

Baumann et al, PRD 37, 3107 (1988)

Spinning superconducting shell?

Precession of a drag-free gyro: Ω is too small

Lab Tests



$$\vec{E} = \frac{qr}{4\pi\epsilon_0 R^3}\hat{r}$$

$$\vec{B} = \frac{2}{3}\mu_0 \vec{M}$$

Within grasp of experiments?

proton as charged, magnetized sphere

spin-flip in the local field

$$\delta\vec{B} = \frac{\mu_0 q \epsilon_\gamma}{20\pi Rc}\left(5\vec{g} + \frac{r^2}{R^2}((\vec{g}\cdot\hat{r})\hat{r} - 2\vec{g})\right)$$

$$\vec{\tau} = \frac{2\mu_0 q\epsilon_\gamma}{5\pi Rc}\vec{\mu}\times\vec{g}$$

$$\Delta\mathcal{E} = \frac{4\mu_0 q\epsilon_\gamma}{5\pi Rc}\mu g \simeq 10^{-34}\epsilon_\gamma \mathrm{GeV}$$

Flambaum et al, PRD 80, 105021 (2009)

Brown et al, PRL 105, 151604 (2010)

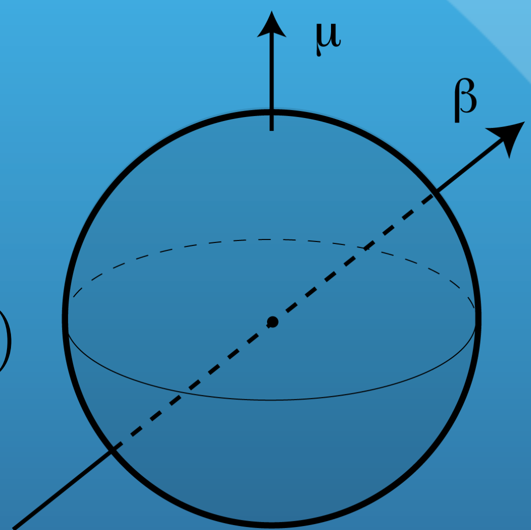
anomalous couplings of neutron?

Lab Tests

Brown et al, PRL 105, 151604 (2010)

$$\Delta\mathcal{E} = -\mu\vec{\beta}\cdot\vec{\sigma}$$

$$< 3.7 \times 10^{-33}\mathrm{GeV}\ (68\%\mathrm{CL})$$



Seek out Mike Romalis' group!

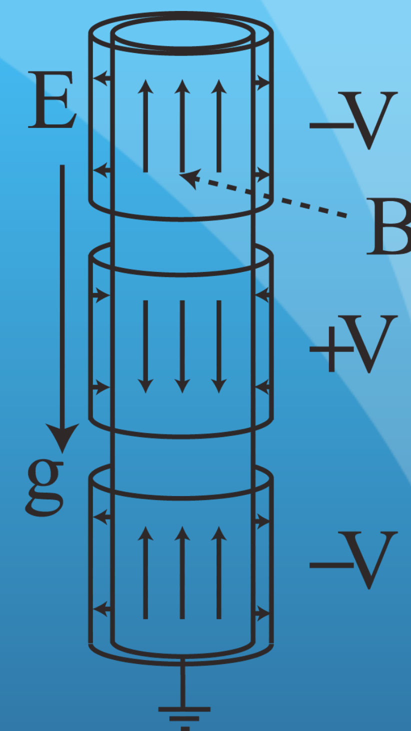
Lab Tests

macroscopic electric field

magnetic field due to the local field

$$\delta B = (1.8 \times 10^{-19}\,\mathrm{T}) \left(\frac{V}{100\,\mathrm{kV}} \right) \left(\frac{\epsilon_\gamma}{5} \right)$$

projected sensitivity $10^{-17} \mathrm{T}/\mathrm{Hz}^{1/2}$



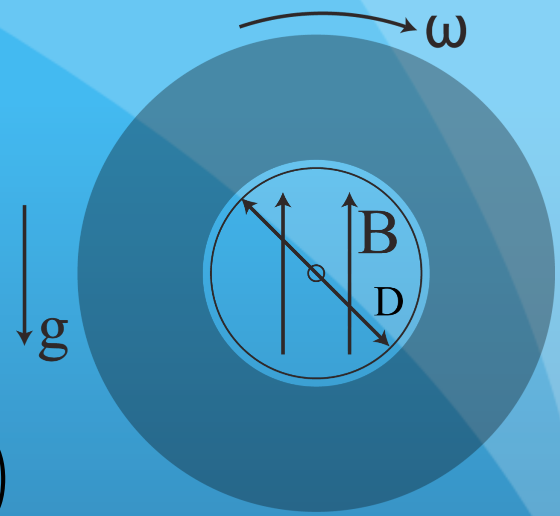
Within grasp of experiments? ***Observe at 1σ after 1 hour integration***

Romalis & RC 2013

Lab Tests

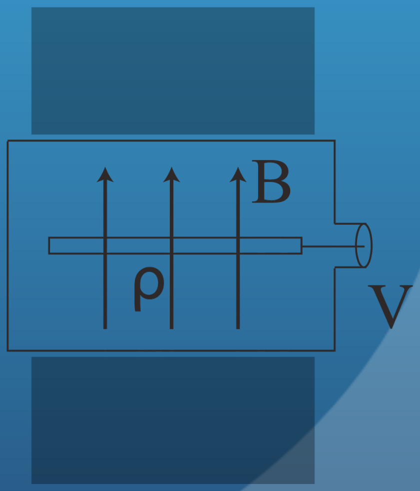
macroscopic magnetized cylinder

voltage due to the local field



$$\Delta V = (0.4\,\mathrm{nV}) \left(\frac{B}{1\,\mathrm{T}}\right) \left(\frac{D}{20\,\mathrm{cm}}\right)^2 \left(\frac{\epsilon_\gamma}{5}\right)$$

projected sensitivity $4\mathrm{nV}/\mathrm{Hz}^{1/2}$



Observe at 4σ after 1 hour integration

Romalis & RC 2013

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