Shining light on dark energy and modifications of gravity

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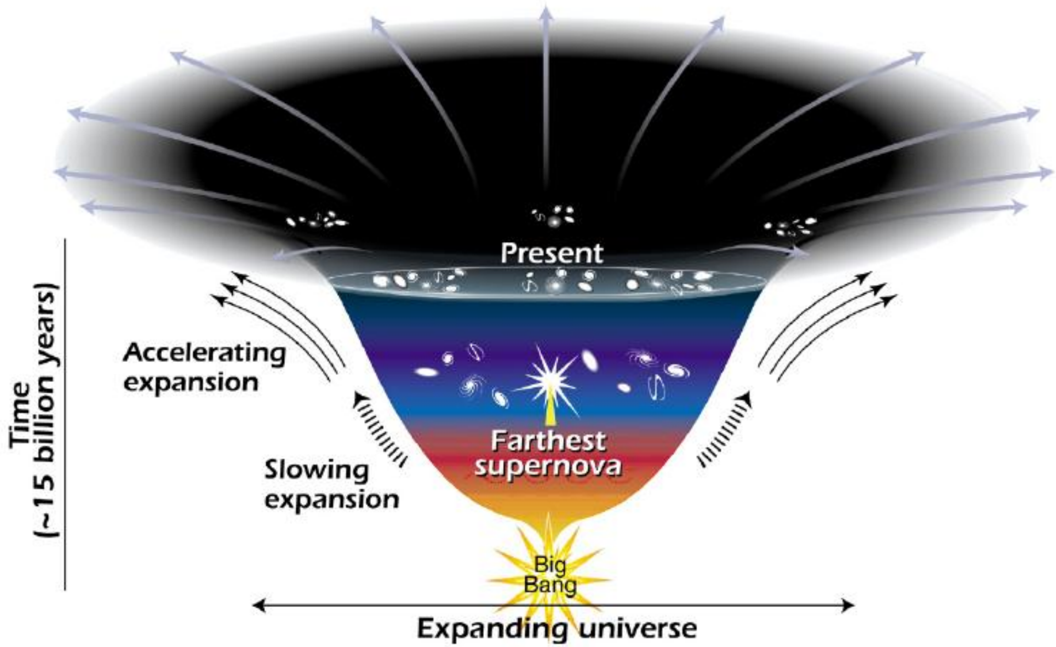
Dark energy and modified gravity

- Almost all proposals directly or indirectly introduce a new light scalar field



- The cause of the acceleration of the expansion of the universe must be coherent across the universe
  - This corresponds to very light masses

What is the most general way of interacting with matter?

- Matter fields couple to an effective metric which depends on the scalar field

$$\mathcal{L} \supset \tilde{g}_{\mu\nu} T^{\mu\nu}$$

- The most general effective metric that can be made from the metric and a scalar field that respects causality and the weak equivalence principle is

$$\tilde{g}_{\mu\nu} = \underbrace{A(\phi, X)}_{\text{Conformal}} g_{\mu\nu} + \underbrace{B(\phi, X)}_{\text{Disformal}} \partial_\mu \phi \partial_\nu \phi$$

$$X = -(\partial\phi)^2/2.$$

- Disformal terms don't give rise to fifth forces

(Bekenstein 1993)

Motivation for disformal terms

- Massive gravity (de Rham, Gabadadze 2010)
  - A massive graviton can be decomposed into
    - One helicity-two mode
    - Two helicity-one modes
    - One helicity-zero mode
- In ghost free formulations of massive gravity matter fields couple to a metric

$$h_{\mu\nu} = \hat{h}_{\mu\nu} + \pi\eta_{\mu\nu} + \frac{(6c_3 - 1)}{\Lambda_3^3}\partial_\mu\pi\partial_\nu\pi$$

  - Where the scale is $\Lambda_3^3 = M_P m^2$.

- Also disformal terms from: quintessence, inflation, varying speed of light…

Energy scales

- A dark energy motivation leads us to expect

$$m \sim H_0 \sim 10^{-33}\ \mathrm{eV}$$

- A modified gravity motivation leads us to expect

$$m \sim H_0 \sim 10^{-33}\ \mathrm{eV}$$

$$M \sim \Lambda \sim M_P \sim 10^{19}\ \mathrm{GeV}$$

- Massive gravity gives

$$m \sim H_0 \sim 10^{-33}\ \mathrm{eV}$$

$$\Lambda \sim M_P \sim 10^{19}\ \mathrm{GeV}$$

$$M \sim \sqrt{M_P m_{\mathrm{grav}}} \sim 10^{-1}\ \mathrm{eV}$$

The Vainshtein Mechanisim

- The scalar field from massive gravity has higher order derivative self interactions

- A massive object gives rise to a non-trivial scalar field configuration
- The self interaction terms mean that the coupling constants for perturbations around the background vary

$$\tilde{\Lambda} = Z\Lambda$$

$$\tilde{M} = Z^{1/2}M$$

$$Z \gg 1$$

Interactions with photons

Scalar Fields Couple to Gauge Bosons

- Conformally coupled scalar fields

$$\tilde{g}_{\mu\nu} = A(\phi) g_{\mu\nu}$$

  - There is no coupling to the kinetic terms of gauge bosons at tree level

$$\mathcal{L} \supset \sqrt{-g}\, g^{\mu\nu} g^{\alpha\beta} F_{\mu\alpha} F_{\nu\beta}$$

- The Standard Model is not conformally invariant
  - The conformal anomaly means that a coupling to photons will always be generated
  - The scale of coupling is undetermined

Interactions with photons

- The general Lagrangian for scalar fields and photons is

$$\mathcal{L}_{\phi,\gamma} = -\frac{1}{2}(\partial\phi)^2 - V(\phi) - \frac{1}{4}F^2 - \frac{\phi}{\Lambda}F^2 - \frac{1}{M^4}\partial_\mu\phi\partial_\nu\phi\left[\frac{1}{4}g^{\mu\nu}F^2 - F^{\mu}{}_{\alpha}F^{\nu\alpha}\right]$$

- Affects the propagation of photons through magnetic fields, causing
  - Changes in polarization
  - Photon number non-conservation

- Then the relevance of the disformal term is controlled by

$$b = \frac{B}{M^2}$$

Propogation through a magnetic field

- This system can be diagonalised and solved

$$\begin{pmatrix} \phi(x) \\ A_y(x) \end{pmatrix} = P \begin{pmatrix} e^{-i\omega(1+\lambda_+)x} & 0 \\ 0 & e^{-i\omega(1+\lambda_-)x} \end{pmatrix} P^{-1} \begin{pmatrix} \phi(0) \\ A_y(0) \end{pmatrix}$$

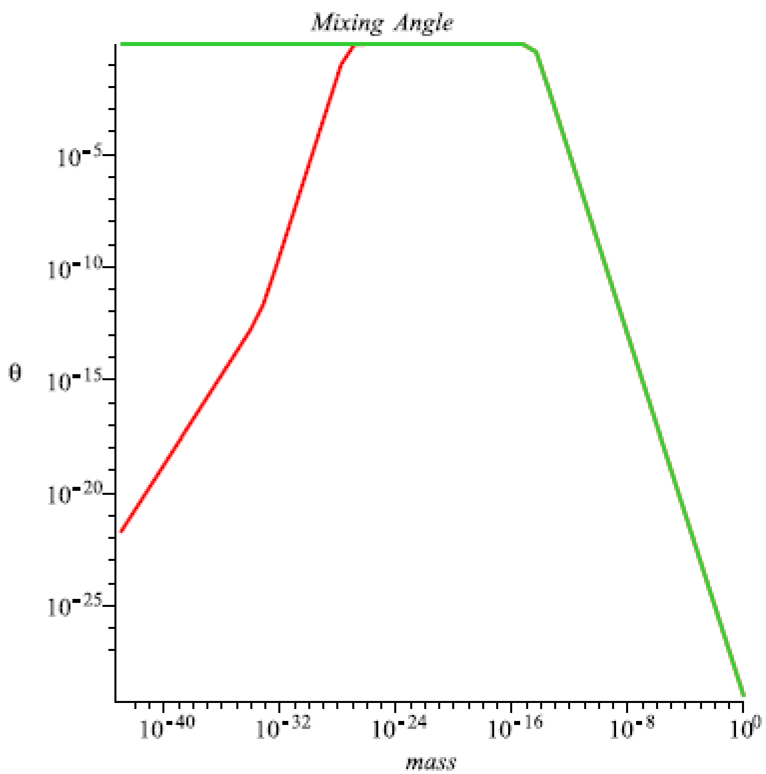
- The mixing matrix is

$$P = \begin{pmatrix} \sin\vartheta & -\cos\vartheta \\ \cos\vartheta & \sin\vartheta \end{pmatrix} \qquad \tan 2\vartheta = \frac{4B}{\Lambda\omega}\sqrt{\frac{1+b^2}{1-a^2}}\left(\frac{m^2}{2\omega^2} - b^2\right)^{-1}$$

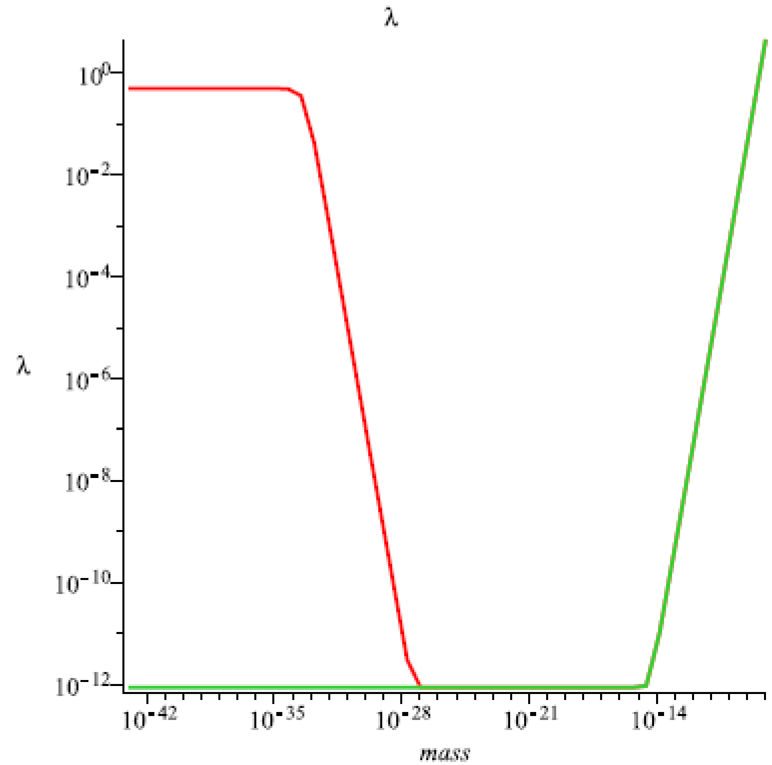
- The eigenvalues are

$$\lambda_\pm = -\lambda(\cos 2\vartheta \mp 1) \qquad \lambda = \frac{1}{2(1+b^2)}\left|\frac{m^2}{2\omega^2} - b^2\right|(1+\tan^2 2\vartheta)^{1/2}$$

Propogation through a magnetic field



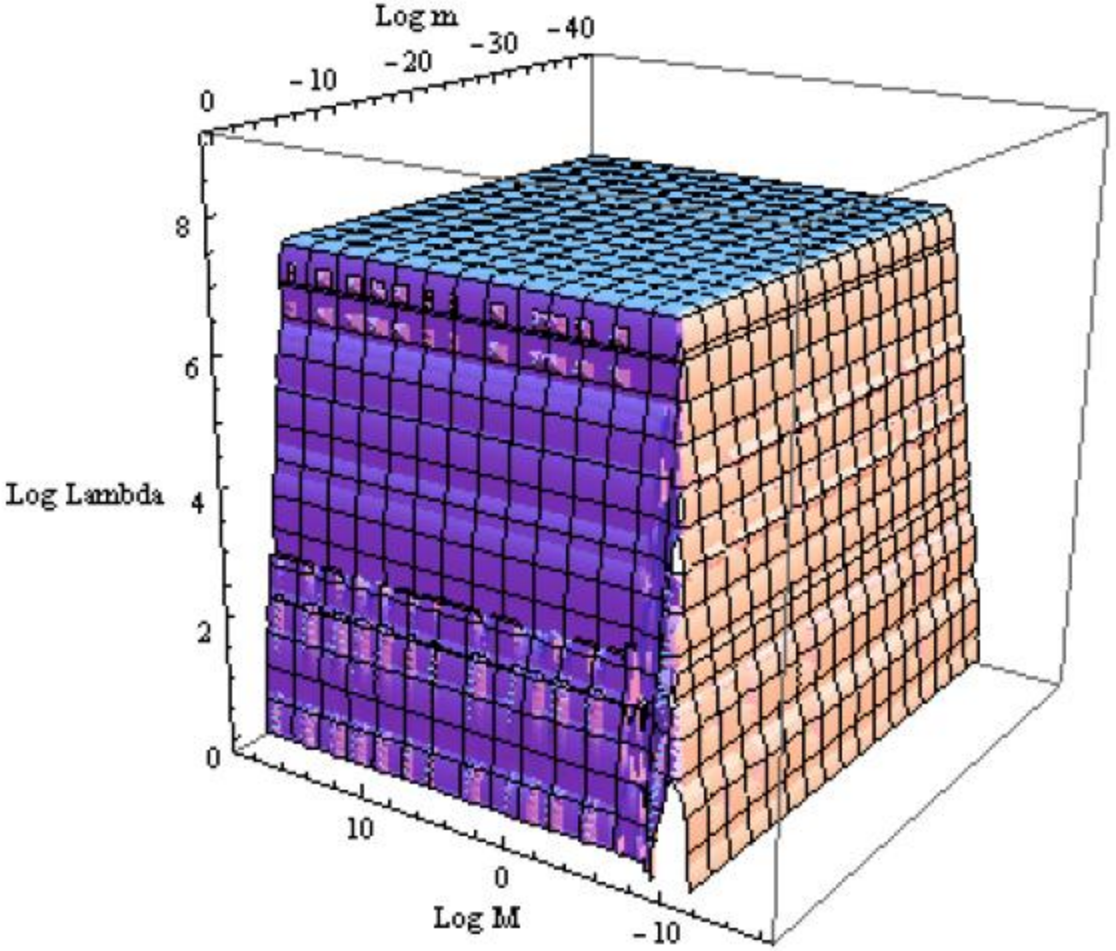
(a) Mixing Angle, ϑ



(b) Oscillation Wavelength, λ

$\Lambda = 10^6$ GeV $\quad M^2 = mM_P \quad B = 5$ Tesla $\quad \omega = 2.33$ eV

Constraints of the ALPS experiment



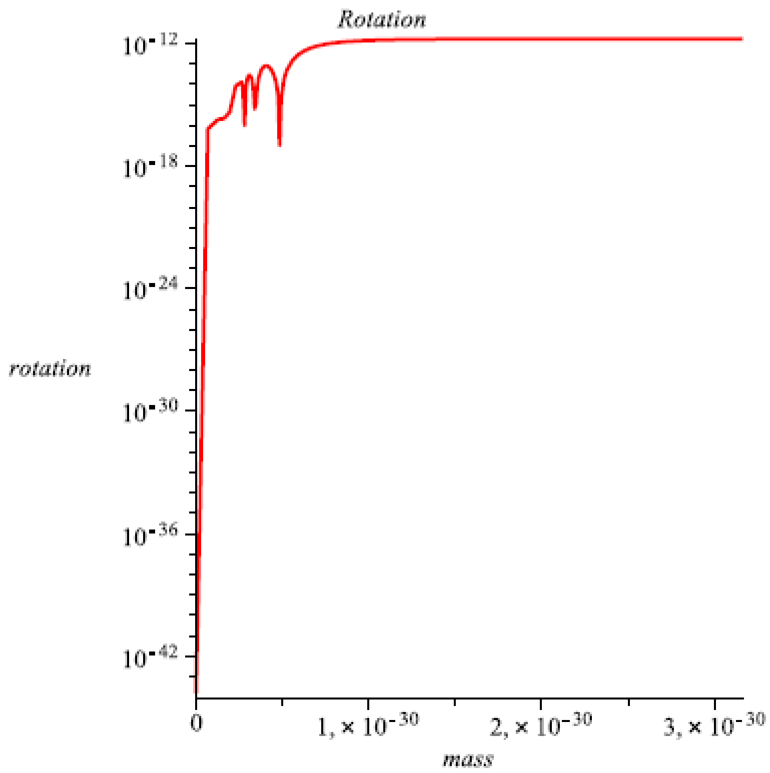
ALPS results from Ehret et al. 2010

Conclusions

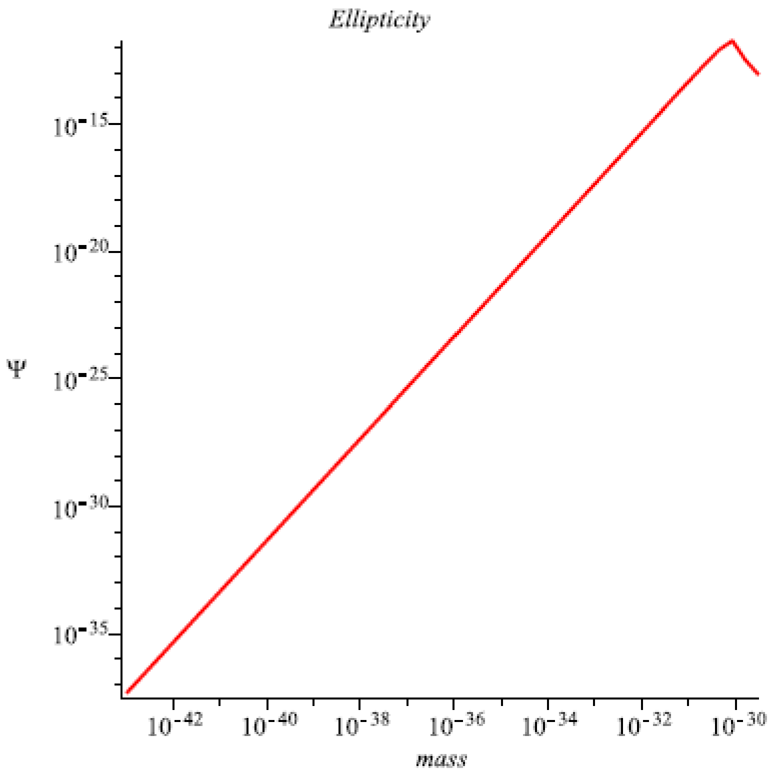
- Dark energy and modifications of gravity introduce new scalar degrees of freedon
- The most general coupling includes conformal and disformal terms
- The disformal terms can couple at a low energy scale
  - eg massive gravity

- High-precision low-energy photon experiments can be used to search for the scalar components of massive gravitons

Scalars at BMV



(a) Rotation

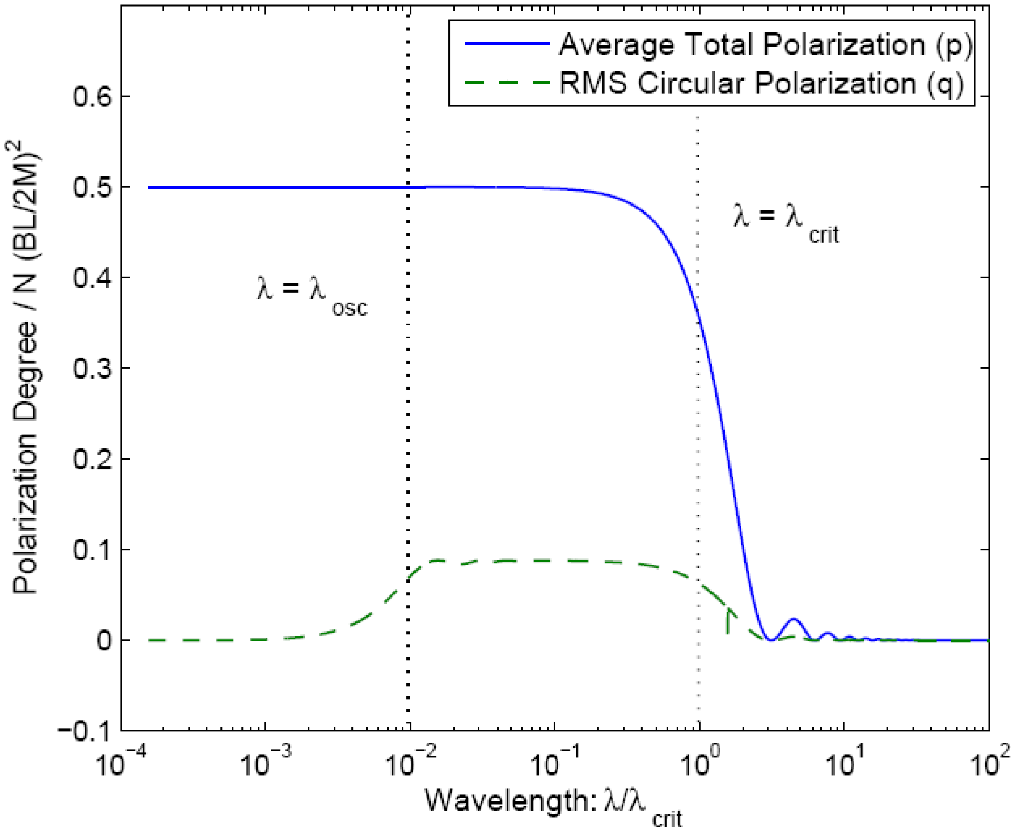


(b) Ellipticity

$\Lambda = 10^6$ GeV $\quad \phi_0 = 10^{-2}\Lambda \quad M^2 = mM_P \quad B = 9$ Tesla $\quad \omega = 1.17$ eV

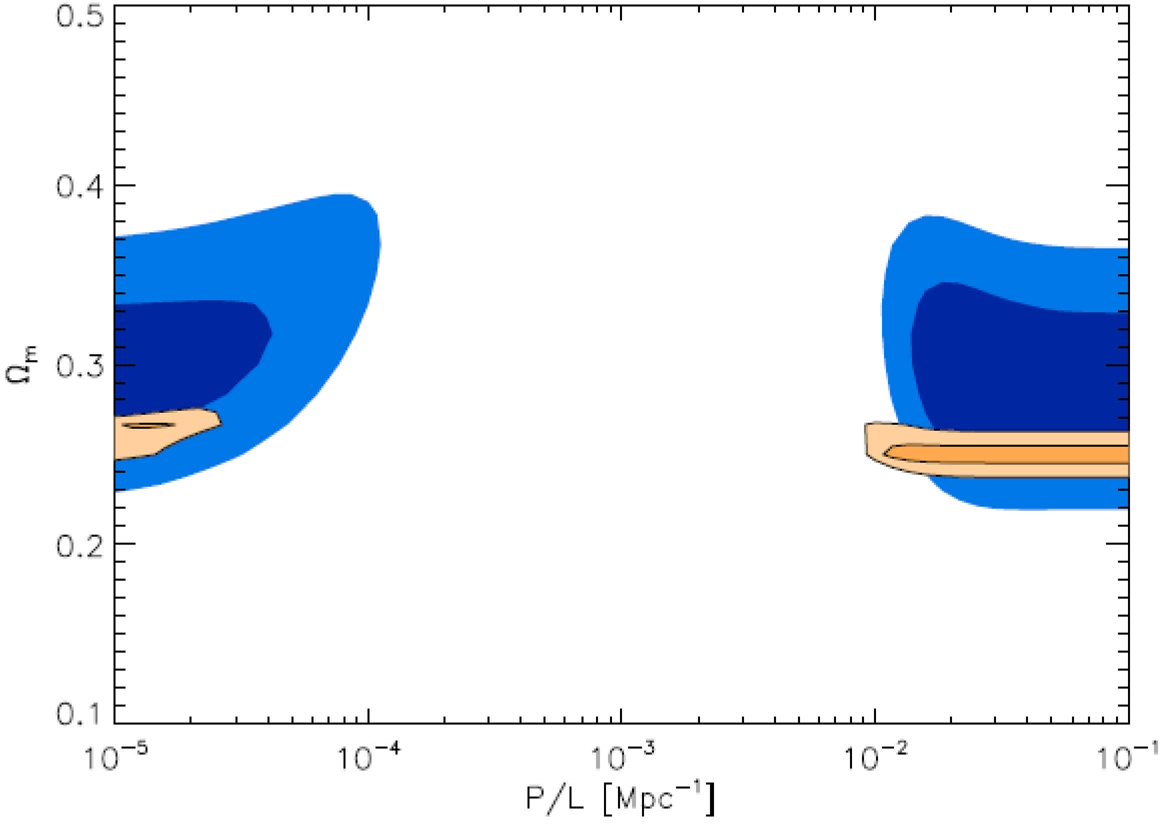
Starlight polarisation

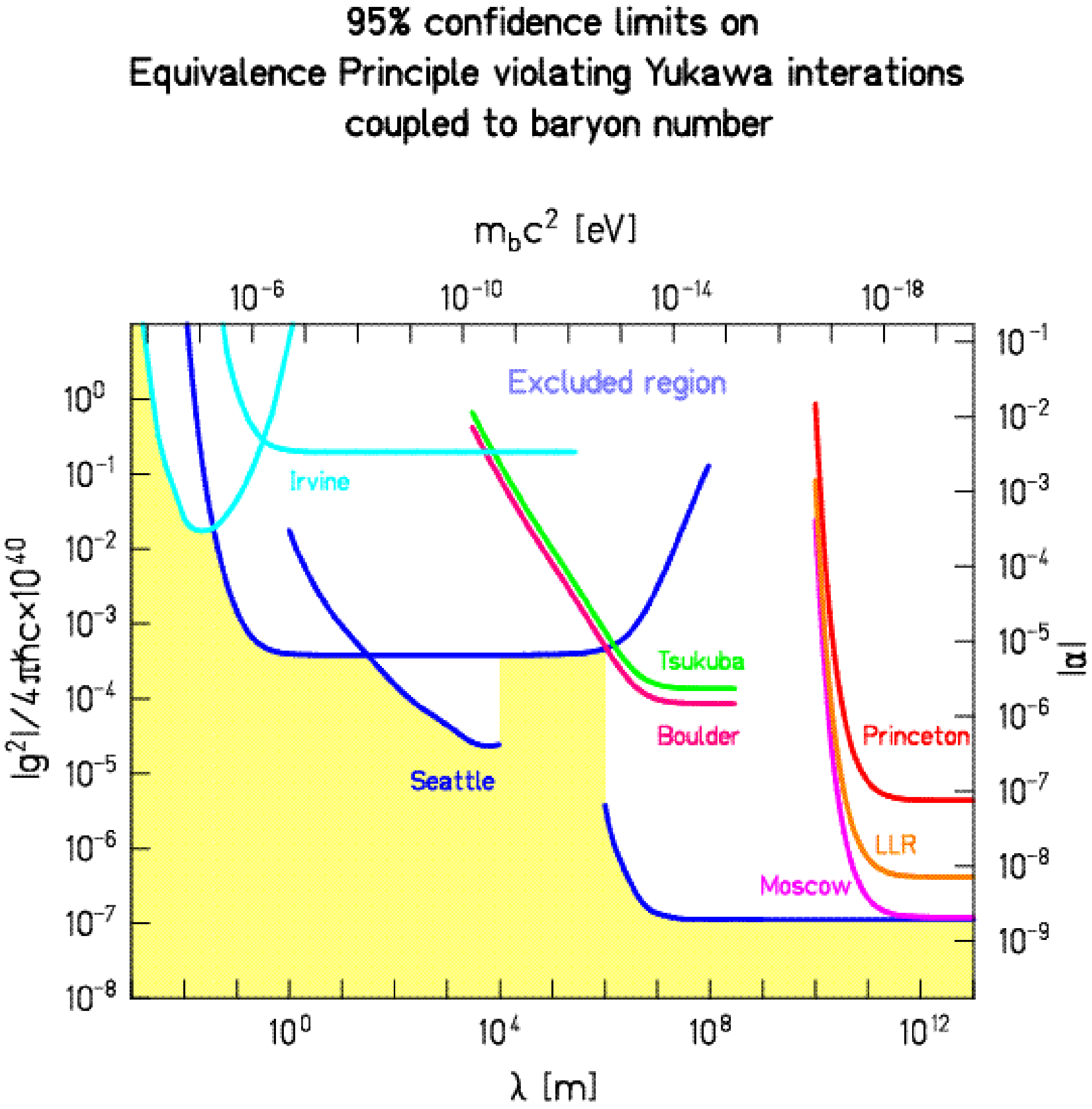
- For a conformal scalar:



Cosmic Opacity

- Violations of photons conservation will look like extra opacity in the universe
- For a conformal scalar





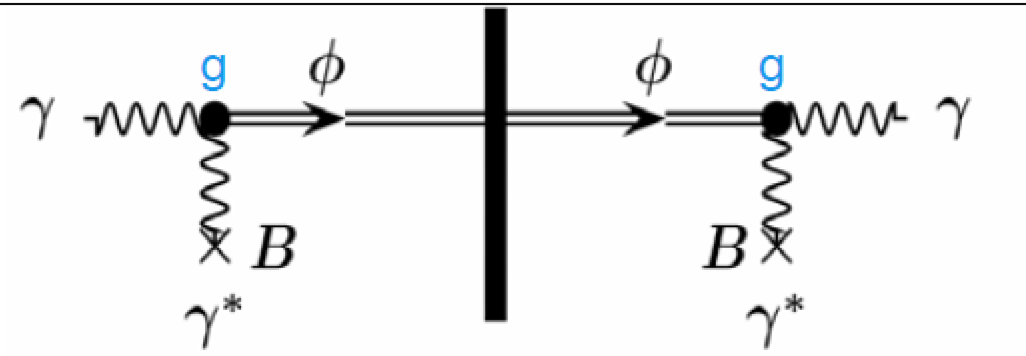
Results of the Eöt-Wash experiment at the University of Washington

Light shining through walls

- The scalar coupling

$$\mathcal{L} \supset \frac{\phi}{M_\gamma} F_{\mu\nu} F^{\mu\nu}$$

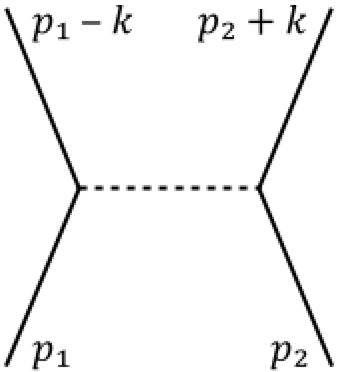
- Leads to light shining through walls



Okun 1982, Skivie 1983, Ansel'm 1985, Van Bibber et al. 1987

Fifth forces

- Light scalar fields mediate new fifth forces



- Forces with conformal couplings seem to be in direct conflict with experimental searches
- To include them we have to either
  - Suppress their coupling to matter with an energy scale above the Planck scale
  - Make the theory non-linear eg chameleons

Fifth forces

- A purely disformal coupling

$$\tilde{g}_{\mu\nu} = g_{\mu\nu} + \frac{2\partial_\mu\phi\partial_\nu\phi}{M^4}$$

$$\mathcal{L}_\phi = -\frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2 + \frac{1}{M^4}\partial_\mu\phi\partial_\nu\phi T^{\mu\nu}$$

- Gives rise to equations of motion

$$\Box\phi - m^2\phi - \frac{2}{M^4}\nabla_\mu(\partial_\nu\phi T^{\mu\nu}) = 0$$

- A static non-relativistic object does not source a scalar field profile, so there are no fifth forces

Fifth forces

- With conformal and disformal terms

$$\tilde{g}_{\mu\nu} = \left(1 + \frac{\phi}{\Lambda}\right) g_{\mu\nu} + \frac{2}{M^4}\partial_\mu\phi\partial_\nu\phi$$

- The equation of motion is

$$\Box\phi - m^2\phi + \frac{T}{\Lambda} - \frac{2}{M^4}\nabla_\mu(\partial_\nu\phi T^{\mu\nu}) = 0$$

- The conformal coupling sources a scalar field profile

$$\phi \approx \frac{M_c}{\Lambda r}$$

Fifth forces

- To compute the force we need the geodesic equation

$$\tilde{u}^\nu \tilde{\nabla}_\nu \tilde{u}^\mu = 0 \qquad \tilde{g}_{\mu\nu}\tilde{u}^\mu \tilde{u}^\nu = -1$$

- We can rewrite this with quantities defined wrt the other metric

$$g_{\mu\nu}u^\mu u^\nu = -1 \qquad a^\mu = u^\nu \nabla_\nu u^\mu$$

$$a^\mu = F^\mu(\phi, \partial\phi, \partial\partial\phi)$$

- For a static, spherically symmetric, non-relativistic source

$$F_r = -\frac{\phi'}{2\Lambda}\left(1 + \frac{\phi'^2}{M^4 + \phi'^2}\right)$$

Motivation for disformal terms

- Disformal inflation
  - Allows for a graceful exit but requires a curvaton

(Kaloper 2004)

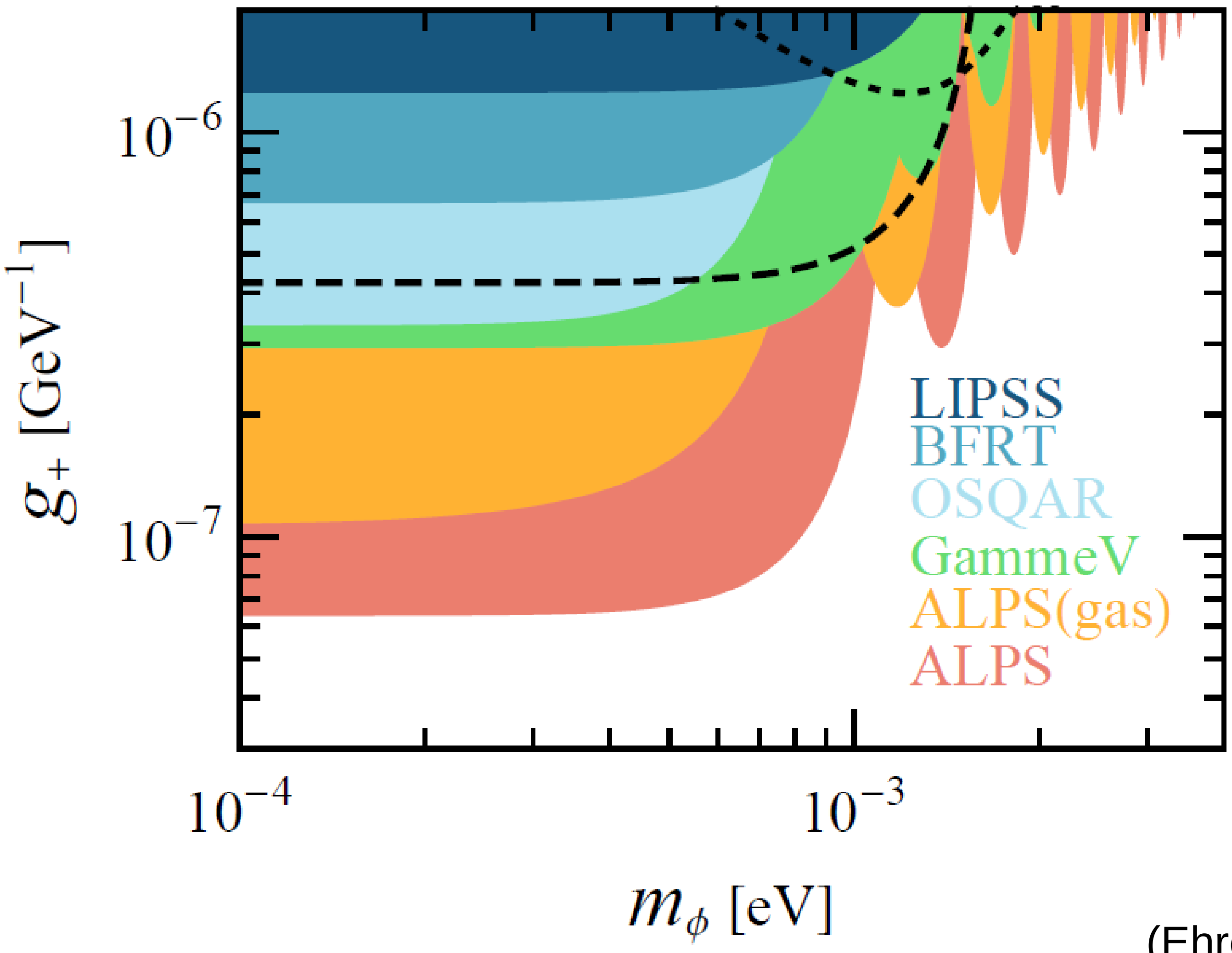
- Disformal quintessence
  - Helps alleviate the coincidence problem
  - No fifth force problems

(Koivisto 2008. Kovisto, Mota, Zumalacárregui 2012)

- Varying speed of light
  - Alternative explanations for the apparent acceleration of the expansion of the universe
  - Now some tension with observations

(Clayton, Moffat 2000. Drummond 1999. Magueijo 2003)

Constraints on the conformal coupling



(Ehret et al. 2010)

Disformal mixing with photons

$$\mathcal{L}_{\phi,\gamma} = -\frac{1}{2}(\partial\phi)^2 - V(\phi) - \frac{1}{4}F^2 - \frac{\phi}{\Lambda}F^2 - \frac{1}{M^4}\partial_\mu\phi\partial_\nu\phi\left[\frac{1}{4}g^{\mu\nu}F^2 - F^\mu{}_\alpha F^{\nu\alpha}\right]$$

- The background solutions

$$A_0 = 0\ ,$$
$$A_i = \frac{1}{2}\epsilon_{ijk}B_j x_k$$
$$V'(\phi_0) = -\frac{2}{\Lambda}B^2$$

- We want to study perturbations around this background

$$\phi \to \phi_0 + \phi\ ,$$
$$A_\mu \to \frac{1}{2}\delta_{\mu i}\epsilon_{ijk}B_j x_k + A_\mu\ .$$

Propogation through a magnetic field

- Equations of motion

$$\Box\phi\left(1+\frac{B^2}{M^4}\right)-\frac{2}{M^4}(\nabla\phi B^2-\partial_i\partial_j\phi B^iB^j)=m^2\phi-\frac{2}{\Lambda}\epsilon_{ijk}B_j(\partial_kA_i-\partial_iA_k)$$

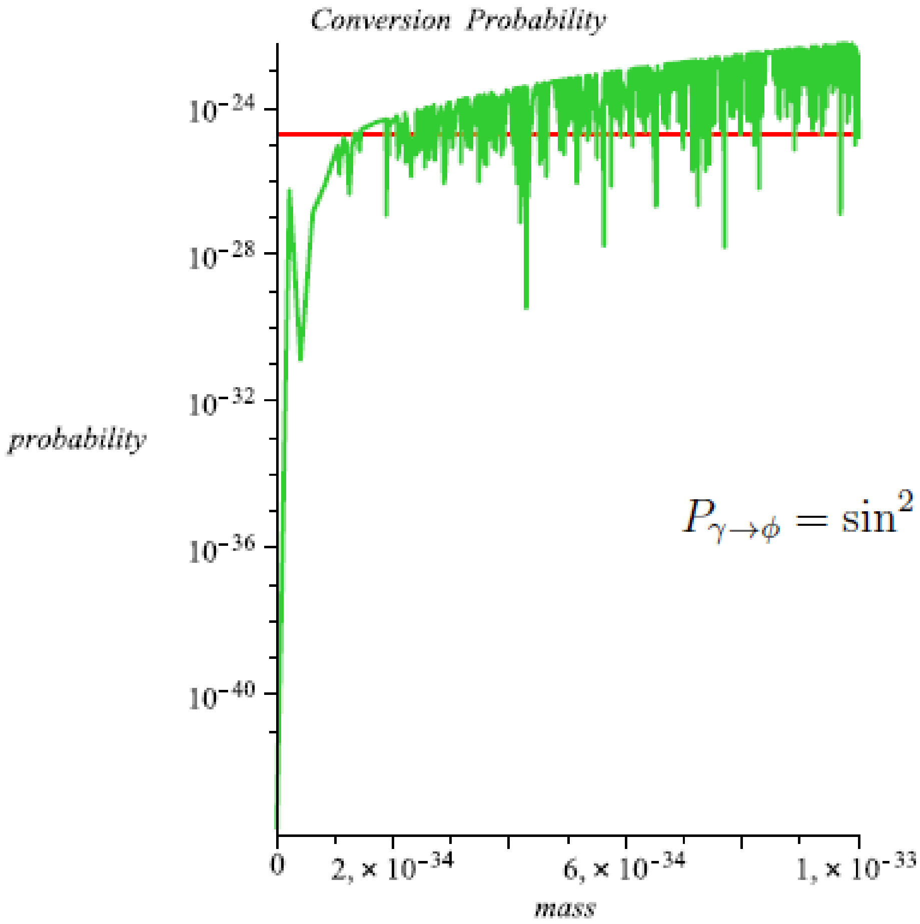
$$\left(1+\frac{4\phi_0}{\Lambda}\right)\Box A_\mu+\frac{4}{\Lambda}\delta_{\mu i}B_j\epsilon_{ijk}\partial_k\phi=0$$

- Only one component of the photon mixes with the scalar

$$\begin{pmatrix}(\omega^2-k^2)+\frac{2k^2b^2-m^2}{1+b^2} & \frac{4Bk}{\Lambda\sqrt{1-a^2}\sqrt{1+b^2}}\\ \frac{4Bk}{\Lambda\sqrt{1+b^2}\sqrt{1-a^2}} & (\omega^2-k^2)\end{pmatrix}\begin{pmatrix}\phi\\ A_y\end{pmatrix}=0$$

$$a=2\sqrt{\frac{-\phi_0}{\Lambda}}\qquad b=\frac{B}{M^2}$$

Probability of mixing



$$P_{\gamma\to\phi} = \sin^2 2\vartheta \sin^2 \lambda\omega x$$

$\Lambda = 10^6$ GeV $\quad M^2 = mM_P \quad B = 5$ Tesla $\quad \omega = 2.33$ eV