Astrophysical Consequences of Chameleon-Photon Mixing

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arXiv:0711.2966
Phys.Rev.D:043009, 2008
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C.B, A.C. Davis and D. Shaw
(to appear)

Outline

- The chameleon model
- Photon-chameleon mixing
- Distance duality
- Supernova brightening
- The effects of the galaxy
- GRBs

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Chameleons

- Scalar-tensor theory of gravity with non-minimal couplings to matter

$$S = \int d^4x\sqrt{-g}\left(\frac{M_{Pl}^2}{2}R - \frac{1}{2}(\partial\phi)^2 - V(\phi)\right) - \int d^4x\,\mathcal{L}_m(\psi_m^{(i)}, g_{\mu\nu}^{(i)})$$

$$g_{(i)}^{\mu\nu} = e^{-2\phi/M_i}g^{\mu\nu} \qquad\qquad V(\phi) = \Lambda^4 e^{\Lambda^n/\phi^n}$$

- Scalar field moves in an effective potential

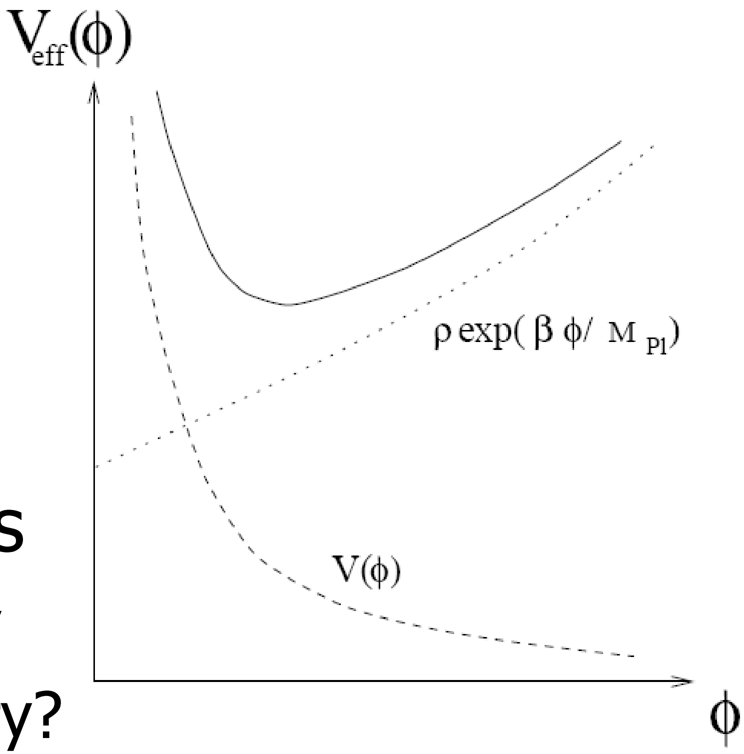
$$V_{eff}(\phi) \equiv V(\phi) + \sum_i \rho_i e^{\beta_i\phi/M_{Pl}}$$

$$\frac{\beta}{M_P} = \frac{1}{M}$$

Khoury & Weltman (2004)

Chameleons

- Mass of the scalar field depends on the local matter density
  - nearly massless on cosmological scales
  - massive field in the atmosphere



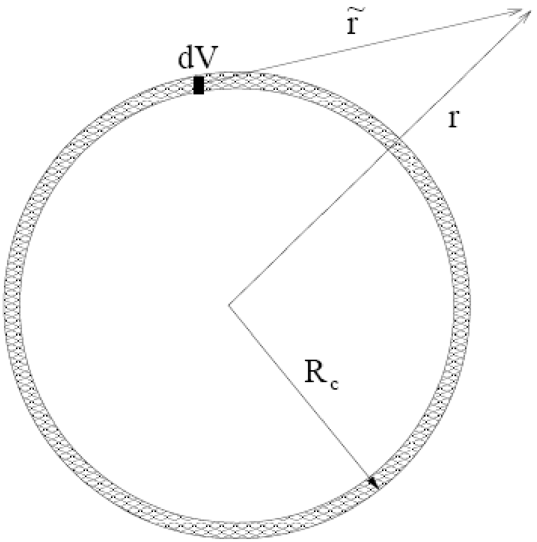
- Candidates for chameleons
  - theories of modified gravity
  - moduli fields in string theory?

Khoury & Weltman (2004)

The thin-shell property

- The chameleon force produced by a massive body is due only to a thin shell near the surface

$$\frac{\Delta R_c}{R_c} \equiv \frac{(\phi_\infty - \phi_c)}{6\beta M_{Pl}\Phi_N} \ll 1$$



- Thin shell
  - deviations from Newton's law $\theta = 6\beta^2 \frac{\Delta R}{R}$
- Thick shell
  - deviations from Newton's law

$$\theta = 2\beta^2$$

Khoury & Weltman (2004)

Chameleon Cosmology

- Attractor Solution
  - follows the minimum of the effective potential
- In agreement with cosmological observations (Redshift of recombination, BBN) if:

$$\Omega_\phi^{(i)} \lesssim \frac{1}{6}$$

- Equation of state
  - early times $\omega \approx 0 \qquad T \gtrsim 10\mathrm{MeV}$
  - late times $\omega \approx -1 \qquad T \lesssim 10\mathrm{MeV}$
- The chameleon is a natural DE candidate!

Brax, van de Bruck, Davis, Khoury, Weltman (2004)

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Photon-Chameleon Mixing

- In the presence of a magnetic field the chameleon couples to photons

$$\mathcal{L}_{int} = \frac{\phi B^2}{M}$$

- In a homogeneous magnetic field

$$\left[\omega^2 + \partial_x^2 + \begin{pmatrix} -\omega_p^2 & 0 & 0 \\ 0 & -\omega_p^2 & \frac{B\omega}{M} \\ 0 & \frac{B\omega}{M} & -m_c^2 \end{pmatrix}\right] \begin{pmatrix} A_\parallel \\ A_\perp \\ \phi \end{pmatrix} = 0$$

- Probability of conversion

$$P(\gamma_\perp \to c) = \frac{4\omega^2 B^2}{M^2(\omega_p^2 - m_c^2)^2 + 4\omega^2 B^2} \sin^2\left(\frac{x\sqrt{M^2(\omega_p^2 - m_c^2)^2 + 4\omega^2 B^2}}{4\omega M}\right)$$

Photon-Chameleon Mixing

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- Achromatic if
  - High energy photons $M|\omega_p^2 - m^2| \ll B\omega$

$$P(\gamma_\perp \to c) \approx \sin^2\left(\frac{L_{dom} B}{2M}\right)$$

    - mixing is maximal
  - Large oscillation length $2\pi L_{dom} \ll L_{osc}$

$$P(\gamma_\perp \to c) \approx \frac{B^2 L_{dom}^2}{4M^2}$$

$$L_{osc} = \frac{4\pi\omega M}{\sqrt{M^2(\omega_p^2 - m_c^2)^2 + 4\omega^2 B^2}}$$

Experiments

- The thin shell property means that the chameleon is consistent with all fifth-force and equivalence principle experiments
- Also consistent with searches for axion like particles (PVLAS, CAST)
- Parameters in the model have to satisfy

$$10^6 \text{ GeV} < M$$

$$\Lambda \sim 10^{-3} \text{ eV}$$

Khoury & Weltman (2004). Brax, van de Bruck, Davis, Mota, Shaw (2007). Brax, van de Bruck, Davis (2007).

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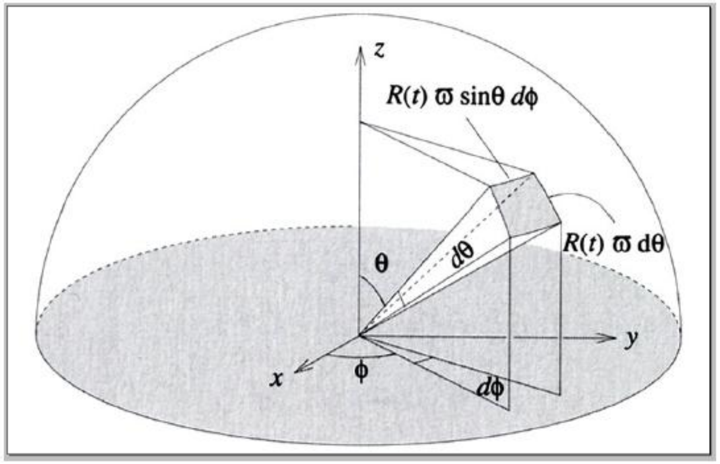
Distance Measurements

- Luminosity Distance

$$F_{\rm obs} = \frac{L}{4\pi d_L^2}$$

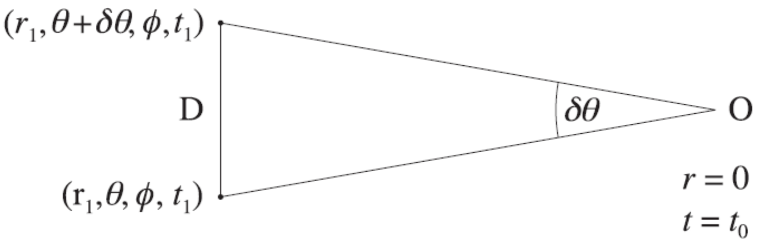
  - Standard Candles
    - Type 1a Supernova



- Angular Diameter Distance

$$d_{\rm A} \equiv \frac{D}{\delta\theta}$$

  - Standard rulers
    - FRIIb radio galaxies
    - Compact radio sources
    - X-ray clusters

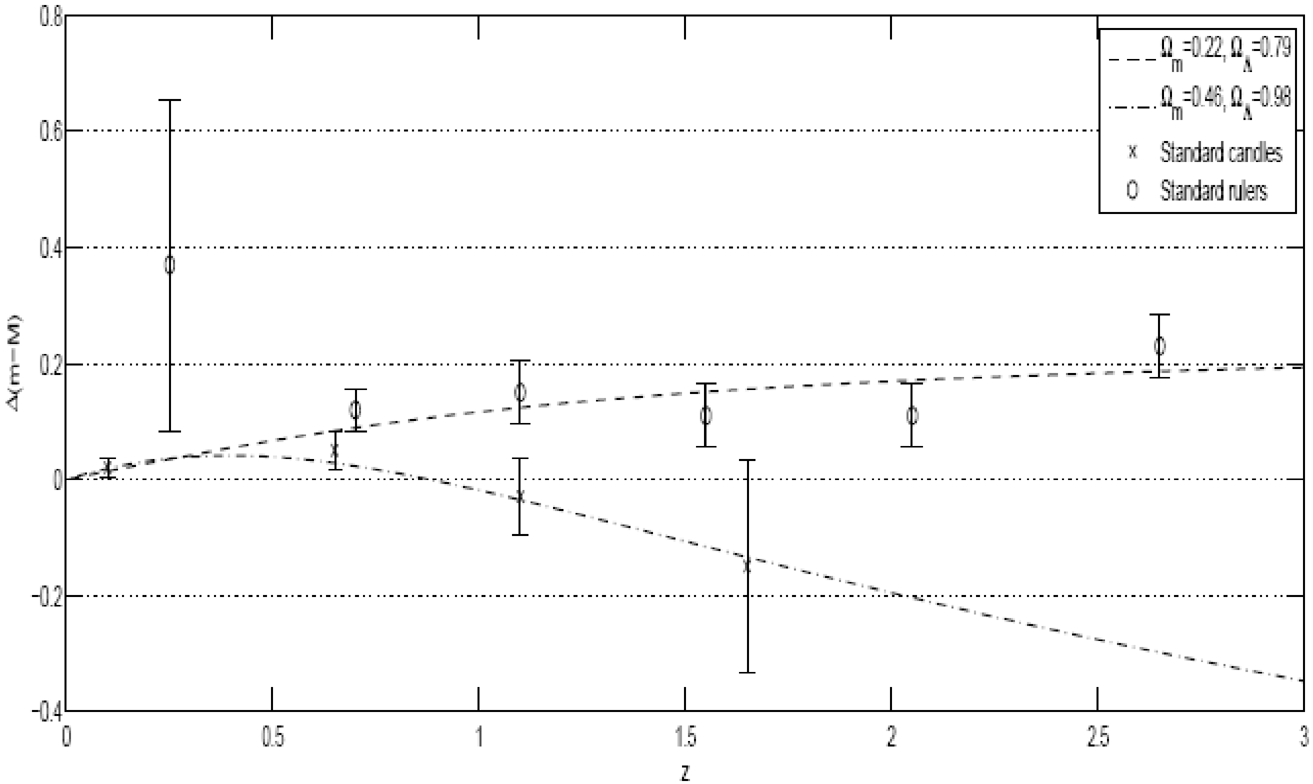


Distance Measurements

- Etherington (1933):
  Distances based on standard candles and standard rulers agree, as long as
  - There is a metric theory of gravity
  - Photons travel on unique null geodesics
  - Photon number is conserved
- Reciprocity relation

$$d_L(z) = d_A(z)(1+z)^2$$

Violation of the reciprocity relation



Riess et al. (2004)

Tonry et al. (2003)

Barris et al. (2004)

Knop et al. (2003)

Daly & Djorgovski (2003)

Daly & Guerra (2002)

Gurvitis (1994)

Jackson & Dodgson (1997)

Jackson (2004)

Allen et al. (2003)

$$m - M = 5\log(d_L) - 25 = 5\log(d_A(1+z)^2) - 25$$

Bassett & Kunz (2004)

Violation of the reciprocity relation

- Possible explanations
  - Photons do not travel on null geodesics (e.g. torsion)
  - Variation of fundamental constants
  - Systematic errors or biases
  - Photon number non-conservation
    - scattering from dust/free electrons
    - photon decay
    - photon mixing with other light states
- But the supernova image is **brighter** than expected

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Varying Background

- Assume:
  - Particles traverse N domains of equal length
  - B is homogeneous in each domain
  - Discrete change in B from one domain to another
  - The magnetic field has a random orientation but equal size in each domain
- Flux of particles

$$
\begin{aligned}
I_c(y) &= \frac{1}{3}(I_c(0)+I_\gamma(0)) + \frac{Q(y)}{3}(2I_c(0)-I_\gamma(0)) \\
I_\gamma(y) &= \frac{2}{3}(I_c(0)+I_\gamma(0)) + \frac{Q(y)}{3}(I_\gamma(0)-2I_c(0))
\end{aligned}
\qquad Q(y) = \left(1-\frac{3P}{2}\right)^{y/L_{dom}}
$$

Photons in the IGM

- Intergalactic medium $\rho_{IGM} \sim 10^{-44}\ \mathrm{GeV}^4$
  $L_{dom} \sim 1\ \mathrm{Mpc} \quad B \lesssim 10^{-9}\ \mathrm{G}$
- Optical Photons $\omega \approx 10\ \mathrm{eV}$
  - High energy regime - oscillations frequency independent if $M \lesssim 10^{10}\ \mathrm{GeV}$
  - System reaches equilibrium state
- CMB Photons $\omega \sim 10^{-4}\ \mathrm{eV}$
  - Low energy regime
  - Probability of conversion small
  - System does not reach equilibrium

$$\begin{aligned} P &\leq 4B^2\omega^2/M^2(\omega_p^2 - m^2)^2 \\ &\lesssim 10^{-6} \end{aligned}$$

Conversion in the Supernova

- Type 1a supernova is the thermonuclear explosion of a white dwarf with mass close to the Chandrasekhar limit
- Simple model
  - Sphere, uniform density, initial radius $R_0 \sim 10^9 \text{ cm}$
  - Expands with outer velocity $v = c/30 \sim 10^9 \text{ cm/s}$
  - Explosion is homologous
  - Photons emitted uniformly throughout the supernova
  - Peak luminosity after 10 days
  - No chameleons are produced by the reactions

Conversion in the Supernova

- Magnetic field $\frac{B_{SN}(t)}{B_{WD}} = \left(\frac{R_{WD}}{R_{SN}(t)}\right)^2$ $10^5 \text{ G} \lesssim B_{WD} \lesssim 10^{11} \text{ G}$
- Oscillation length much greater than coherence length of magnetic field
  - frequency independent oscillations
- Mean free path of photons much smaller than radius of supernova
  - Random walk $N = 3R^2/L_{mfp}^2$ $10^6 \text{ cm} \lesssim L_{mfp} \lesssim 10^{14} \text{ cm.}$
- Probability of conversion in the supernova

$$\begin{aligned} P_{\gamma\to c}(R_{SN}) &\lesssim \frac{3B_{SN}^2 R_{SN}^2}{8M^2} \\ &\lesssim 9.4 \times 10^{32} \left(\frac{B_{WD}^2}{\text{GeV}^2 M^2}\right) \end{aligned}$$

Supernova Brightening

- There is an initial flux of chameleons from the supernova
- In the intergalactic medium

$$P_{\gamma\to\gamma}(y) = \frac{I_\gamma(y)}{I_\gamma(0)} = \frac{2}{2+(1-\frac{3}{2}P_{SN})^N} + Q(y)\left(\frac{(1-\frac{3}{2}P_{SN})^N}{2+(1-\frac{3}{2}P_{SN})^N}\right)$$

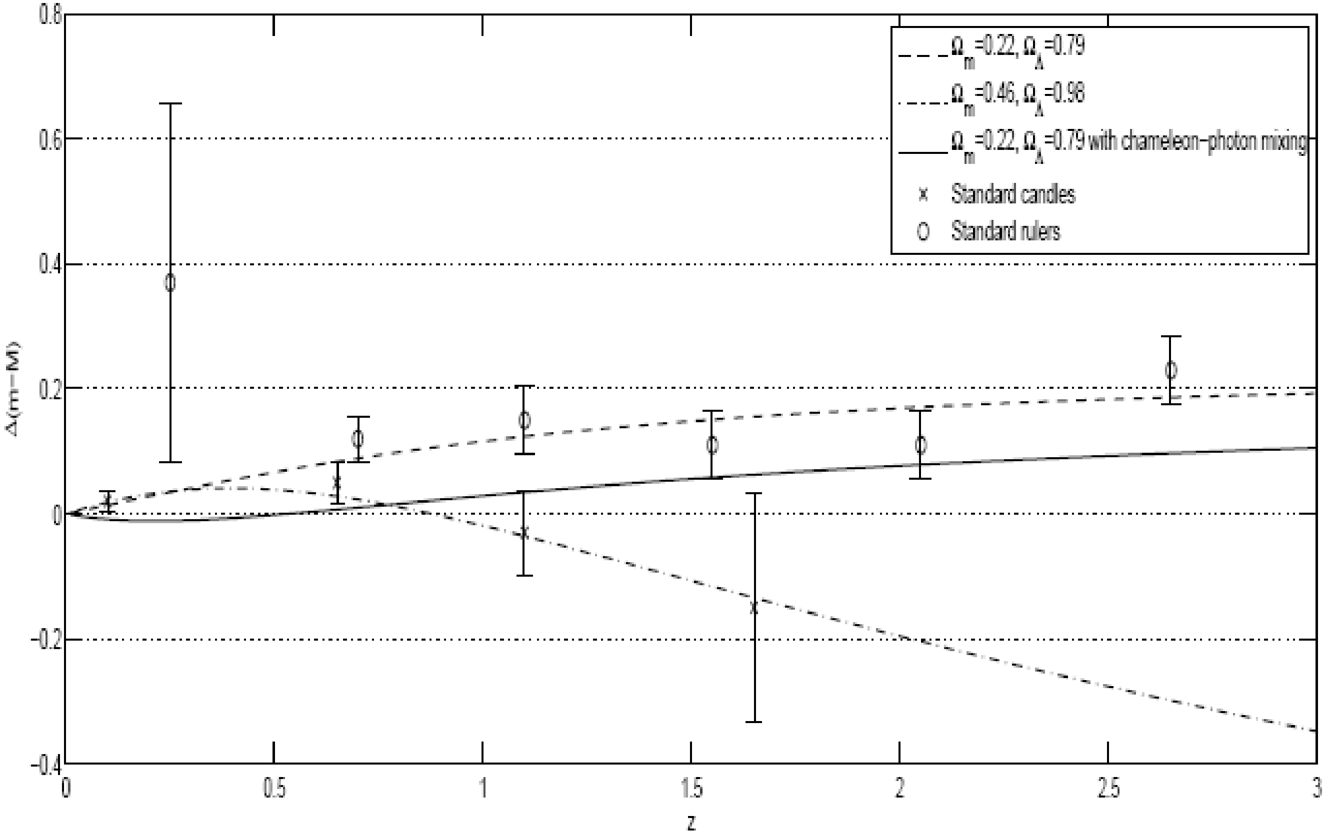
- Have to modify the reciprocity relation

$$d_L(z) = d_A(z)(1+z)^2$$

  - so that $d_L \to d_L/\sqrt{P_{\gamma\to\gamma}}$

Supernova Brightening

- Assuming standard rulers give the correct relation



Supernova Brightening

- Values used:

$$P_{SN} N \approx 0.95$$

$$P_{IGM} \approx 10^{-4}$$

- Which give:

$$B_{WD} \sim 10^{3} \left(\frac{M}{\mathrm{GeV}} \right) \ \mathrm{G}, \quad B_{IGM} \sim 10^{-20} \left(\frac{M}{\mathrm{GeV}} \right) \ \mathrm{G}$$

  - consistent with current experimental bounds
  - more data at high redshift / smaller error bars will significantly improve the constraints

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Mixing in the Galaxy

- For the Milky Way $B = 1\mu\mathrm{G}$ $s = 1$ kpc

  $\rho \sim 10^{-24}$ gcm^{-3} $\omega_p^2 = 4.2 \times 10^{-41}\ \mathrm{GeV}^2$
- Achromatic mixing if

$$7.6 \times 10^8\ \mathrm{GeV} \ll M$$

$$P_G = \left(\frac{L_{dom} B}{2M}\right)^2 = 5.6 \times 10^{17} \left(\frac{M}{\mathrm{GeV}}\right)^{-2}$$

  - Equal to P_{IGM} if intergalactic magnetic field saturates current upper bound
  - System in the equilibrium configuration for low redshift objects seen through the galaxy

Mixing in the Galaxy

- **Prediction:**
  The flux from low redshift objects will be changed by up to 1/3 when seen through the galaxy.

  (compared to an equivalent object seen away from the galaxy)

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Gamma Ray Bursts

- The radiation from GRBs is polarised

$$I_\gamma^{\perp}(y) = \frac{1}{2}(1 - \delta_{\rm pol}(y))I_\gamma(y), \qquad I_\gamma^{\parallel}(y) = \frac{1}{2}(1 + \delta_{\rm pol}(y))I_\gamma(y)$$

$$\Pi \ = \ 100\delta_{\rm pol}\%$$

GRB930131 $35\% \ < \ \Pi \ < \ 100\%$ $3\,{\rm keV} \ < \ \omega \ < \ 100\,{\rm keV}$

GRB960924 $50\% \ < \ \Pi \ < \ 100\%$ $3\,{\rm keV} \ < \ \omega \ < \ 100\,{\rm keV}$

GRB041219a $\Pi = 96^{+39}_{-40}\%$ $100 - 350\,{\rm keV}$

GRB021206 $\Pi = (80 \pm 20)\%$ $0.15 - 2\ {\rm MeV}$

$(\ \Pi > 15\%)$

Gamma Ray Bursts

- Photon-chameleon mixing destroys polarisation

$$\delta_{\rm pol}(y) = Q(y)\delta_{\rm pol}(0)\frac{I_\gamma(0)}{I_\gamma(y)}$$

  where $Q(y) = \left(1 - \frac{3P}{2}\right)^{y/L_{dom}}$

- At the very least for $z \sim 1$ $\omega \approx 100\,\mathrm{keV}$ must have $\Pi > 50\%$ today
- This gives bounds

$$B < 1.02 \times 10^{-20}\,\mathrm{G}\left(\frac{M}{1\,\mathrm{GeV}}\right)$$

$$P_{IGM} < 2.4 \times 10^{-4}$$

Conclusions

- The chameleon model is a scalar-tensor theory with non-minimal coupling
- The chameleon could be dark energy
- Mixing between photons and chameleons could explain the discrepancy between measurements of luminosity and angular diameter distances
- Predict a change in flux for objects seen through the galaxy
- The observed polarisation of GRBs constrains the model