Constraining new fundamental physics with multiwavelength astrometry

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ABSTRACT
While the deflection of light is achromatic in General Relativity, it is not always so in several new-physics models (e.g. certain quantum-gravity and string-inspired models, models with nonminimal photon-gravity coupling or with massive photon etc.). We discuss how parameters of these models may be constrained by precise astrometry at different wavelengths. From published observations of the gravitational lens MG J2016+112, we obtain world-best limits on chromatic gravitational deflection of light (and the unique limit on the photon mass relevant for distance scales $>\text{Mpc}$). We also outline prospects for further improvement of these limits.

Key words: gravitation — astrometry — gravitational lensing: strong — quasars: individual: MG J2016+112

1 INTRODUCTION
Though the conventional model of fundamental physics (which includes the Standard Model (SM) of particle physics to describe electroweak and strong interactions and General Relativity (GR) to describe the gravitational one) performs well in explaining observed phenomena and, up to date, passes most of its experimental tests, there exist clear indications to its incompleteness (for a review, see e.g. Troitsky (2012)), coming both from laboratory experiments (neutrino oscillations) and from astrophysical observations (dark matter, accelerated expansion of the Universe and baryon asymmetry). Numerous theoretical extensions of the standard picture have been suggested which attempt to solve these experimental problems and/or to reduce fine tuning of SM parameters. None of the solutions is presently singled out.

Up to now, GR has successfully passed numerous experimental tests (see e.g. Turyshev (2009) for a review). Measurements of the gravitational deflection of light, performed with high accuracy for astronomical objects visible close to the Sun, is one of these nice tests, an “old and good” one. Gravitational lensing of distant objects is not only a well-established phenomenon but an important practical tool of astrophysics and cosmology, see e.g. Hoekstra et al. (2013). However, yet unobserved, modifications of GR have been theoretically proposed in various contexts. In this study, we attempt to constrain a particular, though wide, class of the proposed extensions of the “SM+GR” fundamental model.

The models we focus on predict frequency dependence of the paths followed by photons in the gravitational field, the so-called “gravitational rainbow”. They include, in particular, the following classes of models.

• Modifications of GR. In general, frequency-dependent corrections arise in any model of quantum gravity, but they are expected to be suppressed by powers of $(\omega/M_{\text{Pl}})$, where $\omega$ is the photon frequency and $M_{\text{Pl}}$ is the fundamental gravity scale (the Planck mass). For the conventional value of $M_{\text{Pl}} \sim 10^{19}$ GeV, they are hardly observable even in the most precise measurements. However, there are numerous models on the market where the gravity scale is many orders of magnitude lower due to the presence of additional space dimensions (for a review, see e.g. Rubakov (2001)). The frequency dependence of photon paths may arise in certain models inspired by string theory (e.g. Ellis et al. (2004)), extensions of the minimal gravitational action (Accioly & Blas 2001), generalizations of the so-called doubly special relativity (Magueijo & Smolin 2004) or models formulated with Finsler geometry (Girelli et al. 2007) etc.

• Nonminimal coupling of photons to the gravitational field, see e.g. Lafrance & Myers (1995) and references therein.

• Models with massive photon. While the SM photon is strictly massless and no indication exists that SM is wrong in this point, a tiny photon mass may consistently appear in extended theories either via the Brout-Englert-Higgs mechanism (Englert & Brout 1964; Higgs 1964) or via the Stückelberg mechanism (Stückelberg 1938). Numerous ex-
Experimental constraints on the photon mass are discussed e.g. by Okun (2006) and Goldhaber & Nieto (2010).

A similar effect may happen in models with axions of quantum chromodynamics or similar particles (Raffelt & Stodolsky 1988) though it is more difficult to constrain because of its magnetic-field dependence.

Previous studies reported scarce limits on the frequency dependence of the gravitational deflection of light. Astrometric limits on the photon mass from the gravitational deflection of quasar radio signals passing close to the Sun (Lowenthal 1973; Accioly & Pasquo 2004) are quoted by the Particle Data Group (Beringer et al. 2012). These limits are not the strongest ones; however, in view of model dependence of many of the constraints, see e.g. Accioly & Pasquo (2004); Adelberger et al. (2007), they are of independent importance. Accioly & Blas (2001) reported constraints on the frequency dependence of the gravitational deflection of light by the Sun in the context of a particular modified-gravity model. We are not aware of any other published constraints.

In this work, we improve significantly the limits mentioned above and sketch prospects for their future improvement.

2 GENERAL ESTIMATES

To put very different models in the frameworks of a single approach, let $\Delta(\omega)$ be the deflection of light measured at frequency $\omega$. Then a rather general, though non-universal, parametrization for the deflection in models we study is (in the particle-physics units where $\hbar = c = 1$ which we use throughout the paper)

$$\Delta(\omega) = \Delta_0 \left( 1 \pm \left( \frac{\omega}{\omega_0} \alpha \right)^{\alpha} \right),$$

where $\Delta_0$ is the deflection predicted by GR, $\alpha$ is a model-dependent power (in the models of interest, $\alpha = \pm 1, \pm 2$) and $M$ is a dimensionless scale expressed through parameters of the model to be constrained.

There are two ways to constrain $M$ for a given $\alpha$. One is to compare positions of the source both with and without the deflection thus measuring $\Delta$ explicitly. Clearly, this approach requires either a moving deflector like the Sun or Jupiter or a moving light source, a spacecraft or a planet. The GR expectation, $\Delta_0$, may be precisely calculated in this case, so even a single measurement of $\Delta$ may constrain $M$. All previously published constraints have been obtained in this way. Being straightforward, this measurement may however be performed in a limited number of cases because of particular trajectories of moving masses in the sky. In the case of the Sun, its own radiation represents a serious background for close separations.

The second option, which is the subject of this study, is to consider cases when the gravitational deflection of light is known to be present but the true direction to the source is unknown (only deflected light is seen). These include observations of light passing by massive objects which do not move in the sky. The method may be applied to a wide variety of sources, at the price of uncertainty in determination of $\Delta_0$. It can be compensated, however, by performing several measurements in one system: for instance, in this way, observations of multiple images in a gravitational lens allow to reconstruct the mass distribution and, indirectly, the true position of the source (assuming GR is valid). For our purposes, we need to perform observations at different frequencies in order to eliminate $\Delta_0$ and to constrain $M$.

Suppose we performed two measurements, $\Delta(\omega_1)$ and $\Delta(\omega_2)$, of the deflection at frequencies $\omega_1$ and $\omega_2$, respectively; $\omega_1 < \omega_2$ (see Sec. 3 for explicit examples). Clearly, we seek tiny effects and $\Delta(\omega_1) \approx \Delta(\omega_2) \approx \Delta_0$. We define $k$ as

$$\Delta(\omega_2) - \Delta(\omega_1) = k \Delta_0$$

and constrain $k$ from observations, $k < k_+$ and $k > k_-$ (one-sided limits at a certain confidence level; we suppose in what follows that GR, $k = 0$, is not excluded so $k_- < 0$ and $k_+ > 0$, true for our examples). In practice, one expects that $|k_\pm| \Delta_0 \sim \epsilon$, where $\epsilon$ is the upper limit on the difference whose expected value is of order the angular resolution. This would be the least model-dependent result; however, to make it more transparent, we assume the form (1) for the corrections to be constrained and express the bound in terms of $M$. To this end, it is convenient to consider separately the models with $\alpha > 0$ (stronger corrections to GR at high frequencies) and $\alpha < 0$ (stronger corrections at $\omega \to 0$).

Following the particle-physics jargon, we will call the former ultraviolet (UV) and the latter infrared (IR) models. An example of an IR model is any theory with massive photon while typical UV models are inspired by quantum gravity.

For a UV model, one then obtains the bound

$$M > |k_\pm|^{-1/\alpha} \left( \frac{\omega_2^\alpha - \omega_1^\alpha}{1/\alpha} \right)$$

while for the IR case, one has

$$M < |k_\pm|^{-1/\alpha} \left( \frac{\omega_1^\alpha - \omega_2^\alpha}{1/\alpha} \right)$$

In Eqs. (3), (4), the choice of the upper or lower sign corresponds to that in Eq. (1).

To obtain order-of-magnitude estimates, consider three energy bands, radio ($\omega \sim 10^{-6}$ eV), optical ($\omega \sim 1$ eV) and X-ray ($\omega \sim 10^{5}$ eV), and assume the best corresponding astrometric accuracies of $\epsilon \sim 10^{-5}$, $10^{-2}$ and 1 arcsecond, respectively. We see, from Eqs. (3), (4), that, in terms of $M$, better constraints on IR models may be achieved by observations at two different radio frequencies while for UV models, the best constraints may be achieved by comparison of radio measurements with either optical or X-ray ones. In any case, these estimates are indicative and we should explore various possibilities for particular sources.

3 OBSERVATIONAL CONSTRAINTS

Here, we sketch two possible practical ways to perform the measurements outlined in the previous section and give, for each of the two, an example of the corresponding constraints obtained with a single object. A more detailed observational study of larger samples of sources will be reported elsewhere.

3.1 Gravitational lenses

High-precision measurements of gravitationally lensed systems are performed with the aim to reconstruct the mass distribution in the lens which in turn may be important for...
cosmological applications. Therefore, there is no lack of observational data, and the precision of measurements at different frequencies is the guiding rule in the data selection. Positions of lensed images depend on the mass distribution in a complicated nonlinear way, and one should expect the same for potential corrections to the GR formula. For this reason, we consider Eq. (1) to be valid for the deflection angle \( \Delta(\omega_\alpha) \) within the small-correction limit, for different values of \( \alpha \) and different signs in Eq. (1).

Table 1. Angular offsets \( \Delta \) (in arc seconds) of the components in the gravitationally lensed system MG J2016+112 at various frequencies (More et al. 2009; Chartas et al. 2001). Numbers in parentheses give error bars in the last digit.

| frequency | 1.7 GHz | 5 GHz | keV |
|-----------|---------|-------|-----|
| B1-A1 (B-A) RA | -3.00574(3) | -3.00595(3) | -2.9(2) |
| DEC       | -1.50363(3) | -1.50394(3) | -1.2(2) |

Table 2. Constraints on the scale parameter \( M \) for different values of \( \alpha \) and different signs in Eq. (1).

| \( \alpha \) sign | limit on \( M \) (95% CL), grav. lens | limit on \( M \) (95% CL), Milky Way |
|-----------------|---------------------------------|---------------------------------|
| -2 +            | <1.6 \times 10^{-9} \text{ eV}   | <2.0 \times 10^{-6} \text{ eV}   |
| -2 -            | <1.6 \times 10^{-8} \text{ eV}   | <2.0 \times 10^{-6} \text{ eV}   |
| -1 +            | <3.2 \times 10^{-12} \text{ eV}  | <6.9 \times 10^{-7} \text{ eV}   |
| -1 -            | <3.2 \times 10^{-10} \text{ eV}  | <6.9 \times 10^{-7} \text{ eV}   |
| +1 +            | >1.9 \times 10^{4} \text{ eV}    | >3.0 \text{ eV}                 |
| +1 -            | >5.2 \times 10^{3} \text{ eV}    | >3.0 \text{ eV}                 |
| +2 +            | >4.4 \times 10^{3} \text{ eV}    | >1.1 \text{ eV}                 |
| +2 -            | >2.3 \times 10^{3} \text{ eV}    | >1.1 \text{ eV}                 |

This limit is better than the one based on the deflection of light by the Sun (Accioly & Paszkó 2004) by two orders of magnitude but is weaker than some other limits (Beringer et al. 2012). However, one should note that this is the only existing limit on the photon mass obtained at the distance scale >Mpc. This is important in view of possible dependence both of the photon mass from the place in the Universe (like in “chameleon” models, e.g. Brax et al. 2004, or in any model with a non-constant profile of the Higgs field) and of the obtained limits from the underlying mechanism, e.g. Adelberger et al. 2007; Accioly & Paszkó 2004; Goldhaber & Nieto 2010.

Turning to UV theories, we, in a similar way, compare measurements at \( \omega_1 = 1.7 \text{ GHz} \) and \( \omega_2 \) (X rays, see Table 1) for data. In X rays, statistical measurement errors are quite large. We determine our limits on \( k \) by the same method. The assumed systematic error is 0.16°. We obtain

\[
\begin{align*}
\alpha & = 0.19 \quad (95\% \text{ CL}, \omega_1 - \omega_2), \\
k & < k_+ = 0.052 \quad (95\% \text{ CL}, \omega_1 - \omega_3).
\end{align*}
\]

The corresponding limits on \( M \) are, again, given in Table 2. These are the first model-independent (and the world-best for particular models) limits on the gravitational deflection of light reported in the literature.

One may wonder whether the radio-interferometric data...
may be used at all to constrain effects of the unusual dispersion since the procedure of reconstruction of the source position assumes the usual dispersion relation for the detected radio waves. To demonstrate that the obtained constraints are reliable, we note the following. Firstly, the gravitational lens we consider does form images of the quasar (they are observed both with and without the interferometric technique). Secondly, the following three conditions allow one to relate the correlation function to the intensity coming from a certain direction: (1) the source is far enough, (2) the emission from different parts of the (extended) source is not coherent and (3) the Huygens’ principle works. All these conditions are satisfied even for the massive photon (in all other cases which we study, the unusual dispersion does not affect the light propagation between the lens and the observer), thus justifying the use of the method in principle. Finally, though the image may be misrepresented in the case of the nonzero photon mass, it is very unlikely that the shift in the image due to reconstruction, which is determined by the geometry of the interferometer, would cancel the anomalous dispersion effect we attempt to constrain, which is governed by the gravitational field of the lensing galaxy. Moreover, in our case this potential reconstruction effect is simply too small: the change of the photon dispersion relation from $|k| = \omega$ to $|k| = \sqrt{\omega^2 - m^2}$ translates into the effective change of the frequency, $\omega \rightarrow \omega (1 + m^2/(2\omega^2))$, in the expression for the field correlation function. For the values of $m$, we constrain and the values of $\omega$ we use, this correction is of order of $3\%$ of the bandwidth (the latter was equal to 8 MHz in More et al. (2009)). This justifies the use of the data in our case.

3.2 Deflection in the Milky Way

Here we discuss another possibility, which at the present precision level gives less restrictive constraints as compared to the gravitational lenses, but may win with the next-generation instruments. The matter distributed in the Milky Way deflects light rays; once the distribution of the matter is known, $\Delta_\omega$ may be calculated. Its value depends on the model of the dark-matter distribution; however, this dependence is not crucial for our purposes, especially if we compare observations at different frequencies, thus eliminating $\Delta_\omega$ in Eq. (1) and leaving it only in the r.h.s. of Eq. (2) where it is multiplied by a tiny coefficient $k$. The measurement of the l.h.s. of Eq. (2) is provided by astrometric measurements of the absolute position of a distant object performed at two frequencies.

To further understand the technique, one should note that absolute multiwavelength astrometry can hardly reach the required level of precision because of the unknown systematic offset between observations at different frequencies. In practice, what is measured is the relative offset of an object under study with respect to some calibrators. Since the calibrators should be bright, they are chosen differently at different wavelengths: for instance, the International Celestial Reference Frame (ICRF; radio) is determined by radio quasars while the Hipparcos (optical) frame is related to nearby stars bright in optical. The positions of the quasars used as ICRF calibrators are therefore not their true positions, but the deflected ones: on its way from the source, the light is deflected by the gravitational field of the Milky Way. It is thus hardly possible to detect any frequency-dependent gravitational deflection by observations of just distant radio sources since the same dependence is expected for calibrators as well. Contrary, the optical reference objects are nearby stars for which we do not expect any significant deflection by the Milky Way (they are simply too close to us). These considerations suggest that to search for the gravitational rainbow, one should measure positions of a source in both reference frames: optical (not deflected) and radio (deflected). Presently, the best way is to study those Hipparcos stars which are radio emitters; an example study was performed by Boboltz et al. (2007). The offset between the optical and radio positions of the “radio star” then constrains $\Delta_\omega$ for a particular reference quasar, while measurements at different radio frequencies would give constraints on the frequency dependence. In particular, Boboltz et al. (2007) measured ICRF positions of 46 Hipparcos stars bright in radio, with the best precision of order a few mas for the angular offset. For instance, one of the most precise measurements was presented for U Sge (Hipparcos number 94910), for which the ICRF minus Hipparcos offsets are 5.1 $\pm$ 7.1 mas in RA, 4.6 $\pm$ 7.2 mas in DEC. Assuming Gaussian errors, this gives $\epsilon \approx 20$ mas at 95% CL for $\omega_1 = 8.4$ GHz, $\omega_2 = 5.7 \times 10^3$ GHz. Using the Galactic mass profile by Navarro, Frenk & White (1996), we directly calculated the estimated GR deflection $\Delta_\omega \approx 80$ mas for this direction (details of the calculation and the analysis of other stars will be presented elsewhere). Eqs. (3), (4) then result in the bounds on $M$ listed in Table 2. These bounds are weaker as compared to those obtained from the gravitational lens because of significantly smaller $\Delta_\omega$ and of the lack of X-ray data.

4 CONCLUSIONS AND OUTLOOK

In this note, we suggested two ways to constrain a certain class of models which result in chromatic gravitational deflection of light. Both methods are related to astrometry at different frequencies; one exploits precise measurements in gravitationally lensed systems while the other one deals with comparative absolute astrometry of defining sources of optical and radio reference frames. We illustrated both methods with simple examples and obtained world-best limits on the chromatic deflection, with the results listed in Table 2.

An interesting application of the study is to constrain the photon mass. Our study of a particular gravitational lens resulted in the limit $m_\gamma < 2.3 \times 10^{-9}$ eV (95% CL). This is not the best ever limit; however, it is the only existing photon-mass constraint relevant for distance scales larger than Galactic.

The limits we derive may be improved either with a statistical analysis of larger data samples (which will be reported elsewhere) or with more precise astrometric measurements. Within the gravitational-lens method, the limits for IR models (including the photon mass) might be improved with more precise multifrequency VLBI measurements of the separation between images of quasars in wide lenses while the key point in improving limits for UV models is in better

2 A single-frequency observation, like that of Boboltz et al. (2007), may also be used at the price of increased systematic uncertainty related to the calculation of $\Delta_\omega$. 

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angular resolution of X-ray imaging. Alternatively, important progress is expected in near future of astrometry with the launch of GAIA which would be able to measure image offsets in optically bright lenses with the precision of \( \sim 20 \mu \)as, overshooting the sensitivity of X-ray studies to \( M \) by an order of magnitude, cf. Eq. (3). An even more dramatic increase of precision is expected for observations of nearby “radio stars” in the GAIA and ICRF frames; this would make the second method competitive with the gravitational lenses. A full-sky analysis of this kind may reveal direction-dependent pattern of differences between the two systems related to deflection of light of ICRF reference quasars by the Milky-Way gravitational field. In any case, these next-generation tests would saturate the precision limit determined by systematic uncertainties.

In case these future studies reveal a significant non-trivial frequency-dependent effect, its interpretation would require a careful study both of its influence on the measurement technique and of potential sources of systematics, including chromatic positions of the quasar cores (e.g. Porcas (2009)), proper motions of the images, effects of standard-physics dispersion (e.g. Bombelli & Winkler (2004)) etc.

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