

Search for gravitationally lensed interstellar transmissions

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We consider interstellar light transmission aided by a gravitational lens. We find that optimal reception efficiency occurs in lensing geometries where the transmitter, lens, and receiver are nearly aligned. We explore various signal detection strategies, employing both existing and emerging technologies. With this study, our understanding of interstellar power transmission via gravitational lensing has significantly progressed. We observe that detection signals from nearby stars, may leverage established photonics and optical engineering technologies, and networks of collaborative astronomical facilities. Our findings support the feasibility of interstellar power transmission via gravitational lensing, directly contributing to the ongoing optical SETI efforts.

I. INTRODUCTION

Interstellar power transmission is very challenging. Even for a collimated laser beam, the large distances involved result in a very small energy received. Consider, a diffraction-limited telescope with aperture d_t yielding the beam divergence of $\theta_0 \simeq \lambda/d_t = 1.00 \times 10^{-6} (\lambda/1 \mu\text{m})(1 \text{ m}/d_t)$. When the signal reaches the receiver at distance z , the beam is expanded to a spot with the radius of $\rho_* \simeq z(\lambda/d_t) \simeq 3.09 \times 10^{11} \text{ m } (z/10 \text{ pc})(\lambda/1 \mu\text{m})(1 \text{ m}/d_t)$. As a result, in the case of a free-space laser power transmission in the vacuum, a telescope with the aperture d_r receives only a small fraction of the transmit power P_T given as $P_R = P_T \pi (\frac{1}{2} d_r)^2 / \pi \rho_*^2$ or

$$P_R = P_T \frac{\pi (\frac{1}{2} d_r)^2}{\pi z^2} \left(\frac{d_t}{\lambda} \right)^2 \simeq 2.63 \times 10^{-24} \left(\frac{P_T}{1 \text{ W}} \right) \left(\frac{1 \mu\text{m}}{\lambda} \right)^2 \left(\frac{d_t}{1 \text{ m}} \right)^2 \left(\frac{d_r}{1 \text{ m}} \right)^2 \left(\frac{10 \text{ pc}}{z} \right)^2 \text{ W}, \quad (1)$$

which yields photon flux of only $Q_R = (\lambda/hc)P_R \simeq 1.32 \times 10^{-5}$ phot/s for $\lambda = 1 \mu\text{m}$. These signals are weak and require both 1) precise and stable transmitter pointing toward us to within $\rho_L/z \simeq \text{few } \mu\text{rad}$ and 2) us having instruments capable of detecting such signals against the challenging optical backgrounds present in our stellar neighborhood.

Therefore, unless there is a significant effort to send us a message using a powerful, focused beam directly aimed at us, detecting faint and transient signals with optical SETI¹ remains extremely challenging.

The situation changes if a transmitter is placed in the focal region of a stellar gravitational lens to benefit from the lens' significant light amplification. Lensing geometries where the light source, the lens, and the receiver are in an approximate alignment maximize efficiency of the interstellar communication links [1]. Given our current technological maturity, we cannot yet position a transmitter in the focal region of the solar gravitational lens. However, we now begun to understand the physics of the interstellar power transmission facilitated by gravitational lensing and are in a position to devise practical strategies to search for the signals originated around nearby stars. These efforts can rely on the already existing technologies, bringing this topic in the realm of advanced photonics and optical engineering.

This paper is organized as follows: In Section II, we present the wave-theoretical tools to describe light propagation in a gravity field. We discuss power transmission via a gravitational lens, introduce major noise sources, and evaluate detection sensitivity. In Section IV we discuss detection strategies. Our conclusions are presented in Section V.

II. EM WAVES IN A GRAVITATIONAL FIELD

We consider a nearby star with mass M_L , radius R_L , and its Schwarzschild radius of $r_g = 2GM_L/c^2$. We assume that an optical transmitter is placed in the focal region of this stellar gravitational lens at a distance $z_0 > R_L^2/2r_g = 547.8 (R_L/R_\odot)^2 (M_\odot/M_L)$ AU from it.

We further assume that a CW laser optical transmitter is facing the lens and is capable of coherently illuminating an annular area around the lens with the radius of $b = \sqrt{2r_g z_0} > R_L$ (see details in [1]). To do that, a diffraction-limited transmitter will have to form an annular beam of light with the mean diverging angle of $b/z_0 = \sqrt{2r_g/z_0} \simeq 7.16 \times 10^{-6} (b/R_L)(R_L/R_\odot)(650 \text{ AU}/z_0)$ rad and pointed toward the receiver behind the lens (see Fig. 1).

¹ See details on the ongoing SETI efforts at https://en.wikipedia.org/wiki/Search_for_extraterrestrial_intelligence

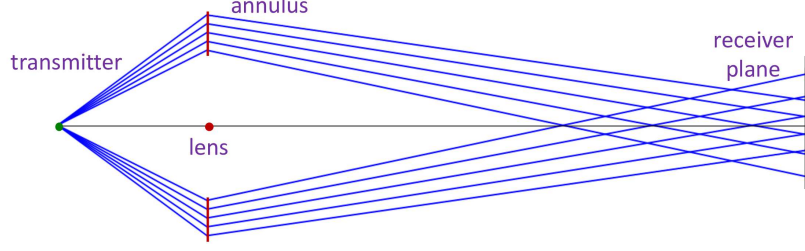


FIG. 1: Beam propagation in a thin lens approximation showing transmitter, lens, annulus, and receiver plane.

When electromagnetic (EM) waves travel in the vicinity of the lens, its gravity causes the waves to scatter and diffract [2, 3]. As a result, after passing by the lens and at a larger distance from it, $z \gg z_0$, the beam will be compressed and nearly collimated by the lens' spherical aberration. If properly designed, the transmitted light will be deposited in the solar system. A solar system observer, looking back at the lensing star, will see the transmitted signal in the form of the Einstein ring. This focusing results in a major increase in the power density of the EM field deposited at the observer's telescope (see discussion in [1]). Below we consider the physics of this effect.

A. Light amplification

We introduce a lens-centric cylindrical coordinate system (ρ, ϕ, z) with its z -axis oriented along the unperturbed direction of the incident wave's propagation (see Fig. 2), given by a unit vector \mathbf{k} . We also introduce a light ray's impact parameter, \mathbf{b} , with $\mathbf{b} \perp \mathbf{k}$. In this coordinate system, the transmitter is positioned at $(0, -z_0)$, while the receiver is on the plane with coordinates (\mathbf{x}, z) and

$$\mathbf{b} = b(\cos \phi_\xi, \sin \phi_\xi, 0), \quad \mathbf{x} = \rho(\cos \phi, \sin \phi, 0). \quad (2)$$

Assuming validity of the eikonal and the thin lens approximations, and considering a uniform surface brightness of the source, the Fresnel-Kirchhoff diffraction formula [4, 5] yields the following expression for the wave's amplitude at the observer (receiver) location

$$A(\mathbf{x}) = E_0 \frac{k}{iz_0 z} \frac{1}{2\pi} \iint d^2\mathbf{b} e^{ikS(\mathbf{b}, \mathbf{x})}, \quad (3)$$

where $k = 2\pi/\lambda$ is the wavenumber and $S(\mathbf{b}, \mathbf{x})$ is the effective path length (eikonal) along the path from the source at $(0, -z_0)$ to the observer's position at (\mathbf{x}, z) via a point $(\mathbf{b}, 0)$ on the lens plane (see Fig. 2) [1]

$$S(\mathbf{b}, \mathbf{x}) = z_0 + z + \frac{\mathbf{x}^2}{2(z_0 + z)} + \frac{z_0 + z}{2z_0 z} \left(\mathbf{b} - \frac{z_0}{z_0 + z} \mathbf{x} \right)^2 + \psi(\mathbf{b}) + \mathcal{O}(b^4), \quad (4)$$

where $\psi(\mathbf{b})$ is the gravitational phase shift that is acquired by the wave as it moves along its geodesic path from the source to the observer. For a monopole lens it has the form [6, 7]:

$$\psi(\mathbf{b}) = \frac{2}{c^2} \int_{z_0}^z dz U(\mathbf{b}, z) = kr_g \ln 4k^2 z z_0 - 2r_g \ln kb. \quad (5)$$

As a result, the wave amplitude on the receiver plane (3) can be written as

$$A(\mathbf{x}) = \frac{E_0}{z_0 + z} \exp \left[ik \left(z_0 + z + \frac{\mathbf{x}^2}{2(z_0 + z)} \right) \right] \cdot F(\mathbf{x}), \quad (6)$$

where $F(\mathbf{x})$ is the amplification factor that is given by the following diffraction integral [1, 6]

$$F(\mathbf{x}) = \frac{ke^{ikr_g \ln 4k^2 z z_0}}{i\tilde{z}} \frac{1}{2\pi} \iint d^2\mathbf{b} \exp \left[ik \left(\frac{1}{2\tilde{z}} \left(\mathbf{b} - \frac{\tilde{z}}{z} \mathbf{x} \right)^2 - 2r_g \ln kb \right) \right], \quad \tilde{z} = \frac{z_0 z}{z_0 + z}. \quad (7)$$

Note that the phase factor under the integral is the Fermat potential along the light path.

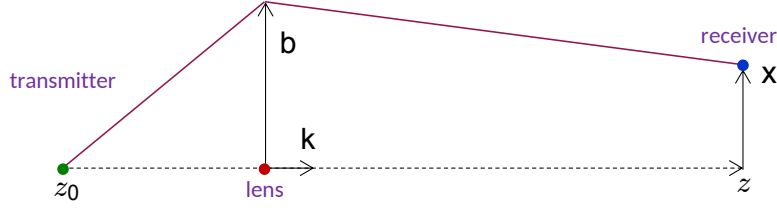


FIG. 2: A lens-centric geometry for interstellar power transmission via gravitational lensing showing transmitter, lens, and receiver. Also shown is the distance from the lens to the transmitter plane, z_0 , and that from the lens to the receiver plane, z .

Benefiting from the axial-symmetry, we integrate over $d\phi_\xi$. Then, using the method of stationary phase [3], we integrate over db , and present (7) as below (see details in [1])

$$F(\mathbf{x}) = \sqrt{2\pi k r_g} e^{i\varphi} J_0\left(k \frac{\sqrt{2r_g \tilde{z}}}{z} \rho\right), \quad (8)$$

where $\varphi = \sigma_0 + k r_g \ln 2k(z_0 + z)$ with $\sigma_0 = -k r_g \ln(k r_g / e) - \frac{\pi}{4}$, see [3], and where J_0 is the Bessel function of the first kind [8].

To consider the light amplification, we determine the point-spread function (PSF), which, in this case, is just the square of the amplification factor (8) [3], namely

$$\text{PSF}(\rho) = 2\pi k r_g J_0^2\left(k \frac{\sqrt{2r_g \tilde{z}}}{z} \rho\right) \simeq 1.17 \times 10^{11} J_0^2\left(k \frac{\sqrt{2r_g \tilde{z}}}{z} \rho\right) \left(\frac{M_L}{M_\odot}\right) \left(\frac{1 \mu\text{m}}{\lambda}\right). \quad (9)$$

Fig. 3 shows the resulting Airy pattern of the transmitting lens projected on the solar system.

Note that an observer, positioned on the optical axis at $z \gg z_0$ from the gravitational lens, will see an Einstein ring around the lens with the radius θ_{ER} given as:

$$\theta_{\text{ER}} = \frac{\sqrt{2r_g \tilde{z}}}{z} \simeq \frac{\sqrt{2r_g z_0}}{z} = 2.46 \times 10^{-9} \left(\frac{M_L}{M_\odot}\right)^{\frac{1}{2}} \left(\frac{z_0}{650 \text{ AU}}\right)^{\frac{1}{2}} \left(\frac{10 \text{ pc}}{z}\right) \text{ rad}. \quad (10)$$

We observe that the first zero of the projected PSF pattern (9) occurs at the distance of

$$\rho_{\text{GL}} = \frac{2.40483}{k \theta_{\text{ER}}} \simeq 155.84 \text{ m} \left(\frac{\lambda}{1 \mu\text{m}}\right) \left(\frac{M_\odot}{M_L}\right)^{\frac{1}{2}} \left(\frac{650 \text{ AU}}{z_0}\right)^{\frac{1}{2}} \left(\frac{z}{10 \text{ pc}}\right), \quad (11)$$

from the optical axis, which is much larger than any modern optical telescope [9]. (Note that this PSF broadening is consistent with the effect of a lens with spherical aberration.) Thus, (9) is good for very small separations, $\rho \simeq \rho_{\text{GL}}$. However, in realistic cases, assuming that the signal is pointed at the Sun, receiver's misalignment may be as much as $\rho \sim 1 \text{ AU} \gg \rho_{\text{GL}}$. In this case, we use the approximation for the Bessel functions for large arguments [8, 10]:

$$J_0^2\left(k \frac{\sqrt{2r_g \tilde{z}}}{z} \rho\right) \simeq \frac{1 + \sin(2k \theta_{\text{ER}} \rho)}{\pi k \theta_{\text{ER}} \rho} \simeq \frac{20.59 \text{ m}}{\rho} \left(\frac{\lambda}{1 \mu\text{m}}\right) \left(\frac{M_\odot}{M_L}\right)^{\frac{1}{2}} \left(\frac{650 \text{ AU}}{z_0}\right)^{\frac{1}{2}} \left(\frac{z}{10 \text{ pc}}\right), \quad (12)$$

where we used the fact that for large arguments $\rho \gg \rho_{\text{GL}}$ the function $\sin(2k \theta_{\text{ER}} \rho)$ is rapidly oscillating; thus, it averages to 0. Using this in (9), the PSF for $\rho \gg \rho_{\text{GL}}$ takes the form

$$\text{PSF}(\rho) \simeq 2.40 \times 10^{12} \left(\frac{1 \text{ m}}{\rho}\right) \left(\frac{M_L}{M_\odot}\right)^{\frac{1}{2}} \left(\frac{650 \text{ AU}}{z_0}\right)^{\frac{1}{2}} \left(\frac{z}{10 \text{ pc}}\right). \quad (13)$$

As a result, the spatial distribution characteristic to the PSF of the transmitting lens (9) and (13) will be encoded in the structure of the transmitted signal [1], guiding our search.

B. Power transmission

To assess the effectiveness of the interstellar power transmission with a stellar gravitational lens, we consider the same energy transmission scenario used to derive (1). We again assume that transmission is characterized by the beam divergence set by the telescope's aperture d_t yielding angular resolution of $\theta_0 \simeq \lambda/d_t =$

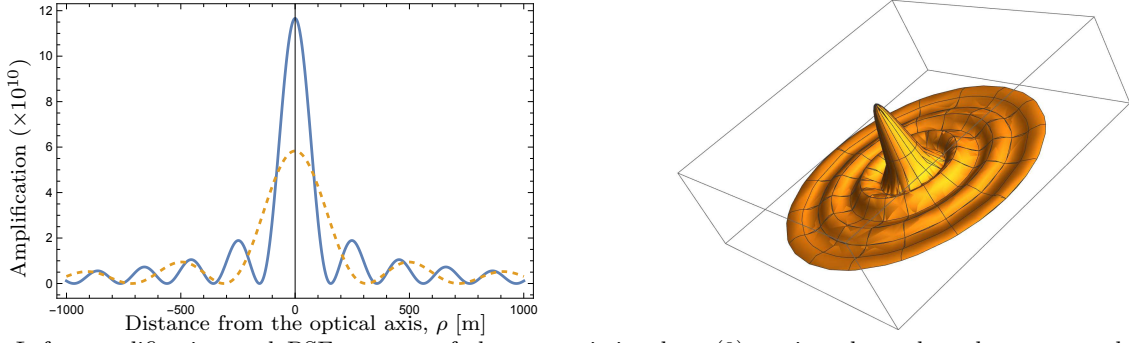


FIG. 3: Left: amplification and PSF pattern of the transmitting lens (9) projected on the solar system plotted for two wavelengths. The solid line represents $\lambda = 1.0 \mu\text{m}$, the dotted line is for $\lambda = 2.0 \mu\text{m}$. Right: a three-dimensional representation of the PSF in the image plane for $\lambda = 1.0 \mu\text{m}$ with the peak corresponding to direction along the transmitter-lens line.

$1.00 \times 10^{-6} (\lambda/1 \mu\text{m})(1 \text{ m}/d_t) \text{ rad}$. When the signal reaches the receiver at the distance of $(z_t + z_r)$ from the transmitter, the beam is expanded to a large spot with the radius of $\rho_* = (z_t + z_r)(\lambda/d_t)$. However, in this case, we need account for the fact that while passing by the lens, the light intensity is amplified according to (9). This is due to the fact that the lens collimates the otherwise diverging beam of light, thus delivering a larger power density to the receiver (see Fig. 1). As a result, a receiver telescope gets a larger fraction of the transmitted power

$$\begin{aligned} P_R^{\text{GL}} &= P_T \frac{\pi(\frac{1}{2}d_r)^2}{\pi\rho_*^2} \text{PSF}(\rho) = P_T \frac{\pi(\frac{1}{2}d_r)^2}{\pi(z_0 + z)^2} \left(\frac{d_t}{\lambda}\right)^2 2\pi k r_g J_0^2(k\theta_{\text{ER}}\rho) \simeq \\ &\simeq 3.06 \times 10^{-13} J_0^2(k\theta_{\text{ER}}\rho) \left(\frac{P_T}{1 \text{ W}}\right) \left(\frac{1 \mu\text{m}}{\lambda}\right)^2 \left(\frac{d_t}{1 \text{ m}}\right)^2 \left(\frac{d_r}{1 \text{ m}}\right)^2 \left(\frac{10 \text{ pc}}{z}\right)^2 \left(\frac{M_L}{M_\odot}\right) \text{ W}. \end{aligned} \quad (14)$$

Comparing (14) and (1), we see that power transmission link aided by a gravitational lens amplifies the received power by $P_R^{\text{GL}}/P_R^{\text{free}} \simeq 1.17 \times 10^{11} J_0^2(k\theta_{\text{ER}}\rho)$, as given by (9).

Assuming that the receiver is near the optical axis, $\rho \simeq \rho_{\text{GL}}$, to estimate the maximum photon flux at the receiver, we compute $Q_{\text{GL}} = (\lambda/hc)P_R^{\text{GL}}$ from (14), yielding

$$Q_{\text{GL}}(\rho) \simeq 1.54 \times 10^6 J_0^2(k\theta_{\text{ER}}\rho) \left(\frac{P_T}{1 \text{ W}}\right) \left(\frac{1 \mu\text{m}}{\lambda}\right) \left(\frac{d_t}{1 \text{ m}}\right)^2 \left(\frac{d_r}{1 \text{ m}}\right)^2 \left(\frac{10 \text{ pc}}{z}\right)^2 \left(\frac{M_L}{M_\odot}\right) \text{ phot/s}. \quad (15)$$

For large separations, $\rho \gg \rho_{\text{GL}}$, we use (12) to transform (15) as below:

$$Q_{\text{GL}}(\rho) \simeq 3.18 \times 10^4 \left(\frac{1 \text{ m}}{\rho}\right) \left(\frac{P_T}{1 \text{ W}}\right) \left(\frac{d_t}{1 \text{ m}}\right)^2 \left(\frac{d_r}{1 \text{ m}}\right)^2 \left(\frac{10 \text{ pc}}{z}\right) \left(\frac{650 \text{ AU}}{z_0}\right)^{\frac{1}{2}} \left(\frac{M_L}{M_\odot}\right)^{\frac{1}{2}} \text{ phot/s}. \quad (16)$$

Therefore, thanks to gravitational lensing, there is a significant photon flux at the receiver. Now we need to consider the feasibility of such a transmission link. For this, we have to evaluate the contribution of major noise sources to the overall detection sensitivity.

C. Major noise source

The angular radius of a stellar lens is $R_L/z = 2.26 \times 10^{-9} (R_L/R_\odot)(10 \text{ pc}/z) \text{ rad}$, which is similar to that of the size of the Einstein ring formed by the transmitted beam of light (10). As the angular resolution of the largest telescopes today [9] is $\lambda/d_r \simeq 1 \times 10^{-7} (\lambda/1 \mu\text{m})(10 \text{ m}/d_r)$, they will not be able to resolve neither the star nor the ring, therefore, the use of a coronagraph is out of the question. Thus, the brightness of that lensing star received by the telescope will be the noise that must be dealt with.

To estimate the relevant photon flux, we consider our Sun. When dealing with laser light propagating in its vicinity, we need to be concern with the flux within some bandwidth $\Delta\lambda$ around the laser wavelength λ , assuming we can filter the light that falls outside $\Delta\lambda$. Taking the Sun's temperature to be $T_\odot = 5772 \text{ K}$, we estimate the solar brightness from the Planck's radiation law and derive the luminosity of the Sun within a narrow bandwidth:

$$L_\odot(\lambda, \Delta\lambda) = 4\pi^2 R_\odot^2 \frac{2hc^2}{\lambda^5 (e^{hc/\lambda k_B T_\odot} - 1)} \Delta\lambda \simeq 2.05 \times 10^{24} \left(\frac{1 \mu\text{m}}{\lambda}\right)^5 \left(\frac{\Delta\lambda}{10 \text{ nm}}\right) \text{ W}, \quad (17)$$

where σ and k_B are the Stefan-Boltzmann and the Boltzmann constants. For a given lens' brightness, L_L , we use (17), to derive the photon flux from the lensing star received by a telescope that is given by $Q_\star = (\lambda/hc)L_L(\lambda, \Delta\lambda)\pi(\frac{1}{2}d_r)^2/\pi z^2$, yielding:

$$Q_\star = 2.71 \times 10^7 \left(\frac{L_L}{L_\odot}\right) \left(\frac{1 \mu\text{m}}{\lambda}\right)^4 \left(\frac{\Delta\lambda}{10 \text{ nm}}\right) \left(\frac{d_r}{1 \text{ m}}\right)^2 \left(\frac{10 \text{ pc}}{z}\right)^2 \text{ phot/s.} \quad (18)$$

Thus, although the stellar flux is very strong (17), it can be significantly reduced by using a narrow bandpass filter at the receiver, centering it at the transmission wavelength (18).

III. DETECTION SENSITIVITY

Quantitative assessment of the signal-to-noise ratio (SNR), is a key to identifying and characterizing received signals. We use results (15) and (18) and estimate the SNR as usual

$$\text{SNR} = \frac{Q_{\text{GL}}}{\sqrt{Q_{\text{GL}} + Q_\star}}. \quad (19)$$

Below, we will consider the detection sensitivity in the noise- and signal-dominated regimes.

A. Noise-dominated regime

When noise dominates the signal, $Q_\star \gg Q_{\text{GL}}$, for a receiver close to the optical axis, $\rho \simeq \rho_{\text{GL}}$, the maximal value of the SNR is given as

$$\text{SNR}_{\text{nd}}(\rho) \approx \frac{Q_{\text{ER}}}{\sqrt{Q_\star}} \simeq 287.43 J_0^2(k\theta_{\text{ER}}\rho) \left(\frac{P_{\text{T}}}{1 \text{ W}}\right) \left(\frac{\lambda}{1 \mu\text{m}}\right) \left(\frac{10 \text{ nm}}{\Delta\lambda}\right)^{\frac{1}{2}} \left(\frac{d_{\text{t}}}{1 \text{ m}}\right)^2 \left(\frac{d_{\text{r}}}{1 \text{ m}}\right) \left(\frac{10 \text{ pc}}{z}\right) \left(\frac{M_{\text{L}}}{M_\odot}\right) \left(\frac{L_\odot}{L_{\text{L}}}\right)^{\frac{1}{2}} \sqrt{\frac{t}{1 \text{ s}}}. \quad (20)$$

Note that (20) was obtained using a modest transmitted power of 1 W. However, that power may be much higher. In fact, modern commercially-available industrial lasers already feature powers of 1–50 kW. Furthermore, coherent beam combination of multiple transmitting laser beams may result in the total transmitted power of up to a few GW and more. In addition, both transmit and receive apertures may be much larger than $\sim 1 \text{ m}$ which was used in estimates above. In these cases, the signal may be much stronger than the noise, outshining the star, requiring a different evaluation of (19), which will be done next.

B. Signal-dominated regime

When signal dominates the noise, $Q_{\text{GL}} \gg Q_{\text{L}}$, (19) yields

$$\text{SNR}_{\text{sd}}(\rho) \approx \sqrt{Q_{\text{GL}}} \simeq 3.92 \times 10^4 \left| J_0(k\theta_{\text{ER}}\rho) \right| \left(\frac{P_{\text{T}}}{1 \text{ kW}}\right)^{\frac{1}{2}} \left(\frac{1 \mu\text{m}}{\lambda}\right)^{\frac{1}{2}} \left(\frac{d_{\text{t}}}{1 \text{ m}}\right) \left(\frac{d_{\text{r}}}{1 \text{ m}}\right) \left(\frac{10 \text{ pc}}{z}\right) \left(\frac{M_{\text{L}}}{M_\odot}\right)^{\frac{1}{2}} \sqrt{\frac{t}{1 \text{ s}}}. \quad (21)$$

Clearly, in a search for transmitted laser signals understanding the SNR is essential. We observe that both estimates (20) and (21) represent handsome levels of detection sensitivity demonstrating feasibility of interstellar power transmission aided by gravitational lensing.

IV. DETECTION STRATEGIES

Detection of laser signals encounters several difficulties. The initial challenge is the highly monochromatic nature of lasers emitting light at a specific wavelength. This unique attribute requires finding the exact λ matching that of an extraterrestrial signal. This also relates to choosing an appropriate width of the narrow band-pass filter, $\Delta\lambda$, to improve the SNR, especially in the case of the noise-dominated regime (20). There is also directionality of laser transmissions. Contrary to radio waves that can disperse omnidirectionally, laser beams are highly focused and narrow. While interstellar gas and dust are largely permeable to near-IR light interstellar laser signals require precise alignment toward Earth to fall within the detection threshold. As a result: although, stellar brightness (18) and

optical background noise are rather well known for each star to be surveyed, the link parameters of the transmitted signal (power, aperture, wavelength, pointing, etc.) used (15) are not available a priori.

Gravitational lensing makes the challenges above less critical, providing a good guidance: The signal that we are looking for has the spatial structure of the PSF of the transmitting lens (9). As such, its structure is known: At typical wavelengths, in the image plane, the spatial frequency of this pattern is on the scale of 100s of meters (as given by (10) and shown in Fig. 3), while its amplitude is proportional to the inverse of the radial distance from the center of the pattern, as seen in (13) as well as in (15)–(16). This is useful for the search.

A. Considering a search campaign

For an interstellar transmission via gravitation lensing, delivery of a transmitter to the focal region of a stellar lens is critical. If that technology is available, then supplying the transmitter with enough propulsion capabilities is similarly plausible. Thus, we may assume that the transmitter is capable of compensating for the relative proper motion between the lens and the Sun, simply directing the signal at the Sun.

The duration over which such lensing event can be observed depends on the width of the received beam and Earth's orbital velocity. To model the dynamics of the event, we assume a vanishing impact parameter and consider the parallactic motion of an Earth-bound observer, $\mu_{\text{rel}} = v_{\oplus}/z$. Under such conditions, the duration of a lensing event, Δt_{ER} , or the time for the receiver to cross the entire diameter of the Einstein ring (occurring twice a year) is

$$\Delta t_{\text{ER}} = \frac{2\theta_{\text{ER}}}{\mu_{\text{rel}}} = \frac{2\sqrt{2r_g z_0}}{v_{\oplus}} \simeq 14.03 \left(\frac{M_{\text{L}}}{M_{\odot}}\right)^{\frac{1}{2}} \left(\frac{z_0}{650 \text{ AU}}\right)^{\frac{1}{2}} \left(\frac{30 \text{ km/s}}{v_{\oplus}}\right) \text{ hr.} \quad (22)$$

Note that this is the duration of the entire lensing event. A full Einstein ring would only be visible if the impact parameter is very small, and even then, only briefly. In that time, the lens will brighten featuring the amplified laser signal in accord with (9). The actual duration of the appearance of the full Einstein ring depends also on the size of the received beam, since it corresponds to the observer traversing its width. The spatial structure of the received beam is that of the PSF of the transmitted lens projected on the solar system, with the width of its main lobe given by ρ_{GL} from (11), which is crossed by Earth in just

$$\tau_{\text{ER}} = \frac{2\rho_{\text{GL}}}{v_{\oplus}} \simeq 0.02 \left(\frac{\lambda}{1 \text{ }\mu\text{m}}\right) \left(\frac{M_{\odot}}{M_{\text{L}}}\right)^{\frac{1}{2}} \left(\frac{650 \text{ AU}}{z_0}\right)^{\frac{1}{2}} \left(\frac{z}{10 \text{ pc}}\right) \text{ s.} \quad (23)$$

The region $\pm\rho_{\text{GL}}$ where the lensing reaches its maximal value of (9) and detection sensitivities (20) and (21). This is a short but very bright event that can be detected with current technology.

What can be observed a photometric campaign is the varying light amplification as the Earth moves relative to direction to the lensing star with angular separation between them in units of the Einstein ring, $u = \theta/\theta_{\text{ER}}$, with θ_{ER} from (10), which may be expressed as

$$u(t, t_0, u_0, \Delta t_{\text{ER}}) = \sqrt{u_0^2 + (t - t_0)^2 / \Delta t_{\text{ER}}^2}, \quad (24)$$

where t_0 is the time of closest alignment and u_0 is the impact parameter of the event, i.e., the angular separation of the source from the lens at t_0 expressed in units of θ_{ER} . The quantity Δt_{ER} represents the characteristic time scale of the event and is given by (22). The objective is to monitor the brightness of the nearby stars for a signature of a microlensing event. The relevant light amplification factor is characteristic for the lensing within the weak interference region of the lens [9, 11, 12], which is given as below:

$$A_{\text{weak.int}} = \frac{u^2 + 2}{u\sqrt{u^2 + 4}}. \quad (25)$$

What is actually observed is the change in the flux of the transmitting lens given as

$$\Delta F(t, t_0, u_0, t_{\text{E}}) = \left(A_{\text{weak.int}}(t, t_0, u_0, t_{\text{E}}) - 1\right) F_0, \quad (26)$$

where $A_{\text{weak.int}}$ is from (25) and F_0 is the nominal flux of the nearby star. In the transmission scenario considered above, the flux ΔF changes twice a year and is correlated with the Earth's orbital motion.

B. Plausible detection strategies

To optimize observations of such transient events, a cooperative telescope network is essential. This network would scan the sky to detect repeatable microlensing events originating at nearby stars with no stellar background that could be responsible. Integrating multiple facilities could enhance spatial resolution, crucial for confident detection and increasing the probability of capturing transmitted signals.

Although photometric measurement capabilities vary among telescopes, any single telescope in the network can perform a broad spectrum of measurements. As a result, a synchronized network of telescopes will be capable of generating detailed imagery of the beam, conducting thorough analyses of its brightness variability.

Although resolving the Einstein rings with the current generation of optical instruments will be challenging, a collaborative network of the astronomical facilities may yield valuable information. With each facility recording brightness measurements and providing its heliocentric position information as a function time, one can use analytical tools available to monitor and study properties of the microlensing event as it unfolds.

We envision using both large telescopes and constellations of small telescopes to capture the photometric data produced by lensing events using the already established photonics and optical engineering technologies. These systems will work in tandem, mutually supplementing observations and offering vital data for predicting events. Several telescopes either in space or both in space and on the ground can be combined in a network to observe the evolving morphology of the Einstein rings as lensing events unfold [9].

As a result, coordinating ground- and space-based telescope observations is important to detect the structure of the PSF of the transmitting lens as the receiver traverses the projected light field. To do that, evaluating the capabilities of current and upcoming astronomical facilities (see [9]) including the James Webb Space Telescope, the Nancy Grace Roman Space Telescope, Euclid, the Vera C. Rubin Observatory's LSST, the Thirty Meter Telescope, and the Extremely Large Telescope, complemented by a network of smaller telescopes is timely, as these facilities may be able to facilitate the search for the faint transient signals transmitted to us by our galactic neighbors.

V. DISCUSSION

Every star is destined to form an Einstein ring. This ring may form naturally with distant sources or through advanced technology, deliberately deployed to send us a message. The position of an Einstein ring around a star, as detailed in (10), depends on our distance to the star, the star's mass, and the transmitter's location. With this information, we can initiate our search for the laser transmissions enabled by gravitational lensing.

Through a synergistic effort, we will soon travel to the focal region of the solar gravitational lens (SGL), enabling direct high-resolution imaging and spectroscopy of exoplanets in our galactic neighborhood [13, 14]. However, before this, we must also survey nearby stars for potential signs of signals sent through gravitational lensing-enabled transmission links. Upon the mission's arrival at the focal region of the SGL, we will have the capacity to observe the surface of exoplanets and initiate meaningful information exchanges with any inhabitants.

To advance such a moment, we considered the propagation of EM waves in the vicinity of a monopole gravitational lens. We explored a scenario with near-perfect alignment among the transmitter, the lens, and the receiver. In this axially-symmetric case, we successfully solved the relevant diffraction integrals analytically, yielding valuable insights.

We explored the case where a transmitter lies in the focal region of a nearby star, with the receiver positioned within our solar system. Although one must account for other light sources near the lens, their impact on the achievable SNRs is expected to be minimal. Given the high sensitivities, we consider the strategies in the search for transmitted signals using existing astronomical facilities or involving development of new facilities dedicated for this purpose.

Our findings reveal that microlensing events, corresponding to laser signals transmitted through nearby gravitational lenses, are transient but notably bright, making them detectable with current instruments. Given their brightness, these microlensing events can be detected and analyzed through a dedicated campaign of photometric observations. Deploying a network of astronomical facilities can enhance detection sensitivity. Consequently, we have demonstrated the feasibility of establishing interstellar power transmission links via gravitational lensing and also our technological readiness to receive those signal—a finding with profound implications in the search for interstellar power transmissions. Now is the right time to design, develop and initiate an appropriate search campaign.

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