Implications of Directed Energy for SETI

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ABSTRACT

We compute the detectability of directed energy sources from distant civilizations that may exist. Recent advances in our own directed energy abilities allow us to foresee our own capability that will radically change our ability to broadcast our presence and hence allow us to ponder the reverse case of detection. In the next few decades we will evolve to the point where we will be able to produce the brightest SED (spectral energy distribution) in the known universe. We show that systems of this type have the ability to be detected at vast distances and indeed can be detected across the entire horizon. This profoundly changes the possibilities for searches for extra-terrestrial technology advanced civilizations. Even modest searches are extremely effective at detecting or limiting many civilization classes. For example, even a single civilization anywhere in our galaxy that is of comparable technological advancement to our own can be detected with near unity probability with a small cluster of 0.1 m telescopes on Earth while a 1 m class telescope has the ability to detect even a single civilization anywhere in the Andromeda galaxy. We compare ground based surveys with aperture sizes from 1mm (smaller than a cell phone optic) to 1 m (modest telescope) and compute blind transmission and blind reception probabilities. We propose a search strategy, using small Earth based telescopes, that will observe more than 10^{12} stellar and planetary systems with possible extensions to more than 10^{20} systems allowing us to test the hypothesis that other similarly or more advanced civilization with this same capability, and are broadcasting, exist. We show that such searches have unity probability of detecting even a single comparably advanced civilization anywhere in our galaxy within a relatively short search time (few years) IF that civilization adopts a simple beacon strategy we call "intelligent targeting", IF that civilization is beaconing at a wavelength we can detect and IF that civilization left the beacon on long enough for the light to reach us now. In this blind beacon and blind search strategy the civilization does not need to know where we are nor do we need to know where they are. This same basic strategy can be extended to extragalactic distances. Portions of this paper come from our recent paper entitled "The Search for Directed Intelligence".

Keywords: SETI, Search for Extra Terrestrial Intelligence, DE-STAR, Directed Energy, Laser Phased Array

1. INTRODUCTION

One of humanities most profound questions is "are we alone". This continues to literally obsess much of humanity from the extremely diverse backgrounds and interests from scientific, philosophical and theological. Proof of the existence of other forms of life would greatly influence all of humanity. The great difficulty in finding life is that our physical exploration (planets physically explored) is woefully inadequate with a fractional search currently of order 10^{-20} since the number of planets, based on the recent Kepler data and the estimated number of stars, in our universe is estimated to be of order 10^{20-24} and we have visited of order unity planets. For the foreseeable future we lack the ability to physically search much beyond this. A detection of an extra-terrestrial civilization would forever change humanity while an upper limit based on our assumptions has only a modest effect. Portions of this paper come from our recent paper entitled "The Search for Directed Intelligence".

Planetary Defense and Space Environment Applications, edited by Gary B. Hughes, Proc. of SPIE
Vol. 9981, 99810H · © 2016 SPIE · CCC code: 0277-786X/16/$18 · doi: 10.1117/12.2238212

2. CIVILIZATION CLASSES AND SIGNAL LEVEL

We assign the same civilization classifications (denoted as S) scheme as we use for the DE-STAR array classification where the civilization class indicates both the power level and beam size of the emitted laser. We assume a standard DE-STAR (S) with nominal Earth like solar illumination (F_E = 1400 W/m^2 at the top of the atmosphere) and a square laser array size (d) where $d(m) = 10^S$ and beam divergence full angle $\theta = 2\ \lambda(m)/d(m) = 2\ \lambda 10^{-S}$ and solid angle $\Omega(st) = \theta^2 = 4\ \lambda^2\ 10^{-2S}$ for small angles. The power is assumed to be continuous wave (CW) rather than pulsed with a value of approximate $P(kw) = 1.4\ \varepsilon_c\ 10^{2S}$ where ε_c is the conversion efficiency of solar to laser power of (eff_{pv} * eff_{de}).

The critical observable is the flux (W/m^2) at the (Earth) telescope and this is the transmit power P (W)/$L^2\,\Omega$ where L(m) is the (luminosity) distance. Thus the critical ratio at given distance is P(W)/Ω(st). For a DE-STAR system of class S we have:

$$P(W)/\ \Omega(st) = F_E\ \varepsilon_c\ 10^{2S}/4\ \lambda^2\ 10^{-2S} = 1400\ \varepsilon_c\ 10^{2S}/4\ \lambda^2\ 10^{-2S} = 350\ \varepsilon_c\ \lambda^{-2}\ 10^{4S}$$

We can thus calculate the civilization class S from any system with a given power and solid angle, even if not a DE-STAR class system, as:

$$S = ¼\ Log_{10}\ ([P(W)/\ \Omega(st)]/(\ 350\ \varepsilon_c\ \lambda^{-2})) = ¼\ Log_{10}\ ([P(W)/\ \Omega(st)]/(\ 175\ \lambda^{-2})).$$

We assume ε_c = 0.5 total conversion efficiency of solar (stellar) illumination to laser output. This is about a factor of two higher than our current state of the art for CW systems (present efficiency of concentrated space solar is 50% and laser efficiency is above 50% for the most efficient systems).

For reference a class 0 civilization would possess the equivalent of a 1 meter diameter optical system transmitting approximately 1 kW while a class 4 civilization would be able to build a 10 km array with transmitting approximately 100 GW and a class 11 civilization would be able to harness the power of a star like our Sun and convert it into directed energy. A class 5 civilization would be similar in this sense to a Kardashev Type I while a class 11 civilization would be similar in this sense to a Kardashev Type II or similar to civilization that can harness a typical star. We are currently about a class 1.5 civilization and rising rapidly. We already have the technological capability to rise to a class 4 civilization in this century should we choose to do so. As one example, two class 3 and above civilizations can "see" each other across the entire horizon modulo the time of flight. Here we use the term (entire horizon) to refer to high redshift galaxies we feel have had sufficient time to develop life. As an example a 1 km array with 100 GW of optical power at 1.06 μm (one of the proposed Breakthrough Starshot array options) would be a class S = 3.54.

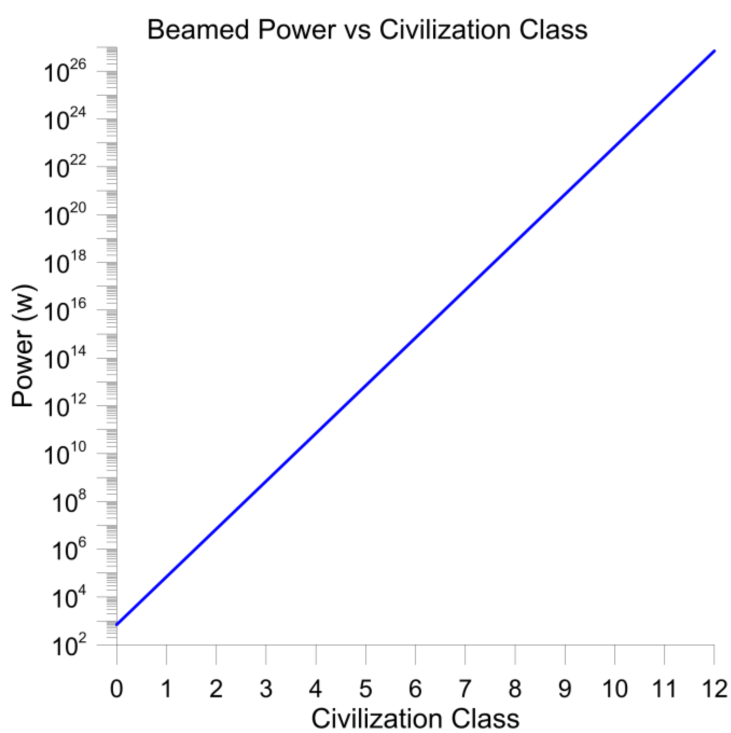

Figure 1 – Civilization class and laser emitted power level (CW).

Flux and Magnitude Equivalents vs. Civilization Class and Distance - We can now compute the flux at the Earth from a distant civilization which we show in Figure 2. The distances are the effective "luminosity distance" which at non cosmological distances is simply the normal Euclidean distance we are used to measuring. At cosmologically significant distances we need to use the cosmological correction reflecting the geometry of our universe. This is discussed and computed below. It is helpful to also think of the received flux in terms of the equivalent photometric magnitude that is commonly used in astronomy. We show this in Figure 3 as a rough indication of how "bright" the signal is. The equivalent magnitude is computed as if the signal were uniformly distributed over the typical photometric bandwidth of R ~4. Of course the laser lines we look for are much narrower so we have vastly less background that in a photometric band. Nonetheless this is instructive when comparing to the common language of magnitudes in astronomy. **As can be seen at the distance of the typical Kepler planets (~1 kly distant) a class 4 civilization (operating near 1 μm) appears as the equivalent of a mag~0 star (i.e., the brightest star in the Earth's nighttime sky), at 10 kly it would appear as about mag ~5, while the same civilization at the distance of the nearest large galaxy (Andromeda) would appear as the equivalent of a m~17 star. The former is easily seen with the naked eye (assuming the wavelength is in our detection band) while the latter is easily seen in a modest consumer level telescope.**

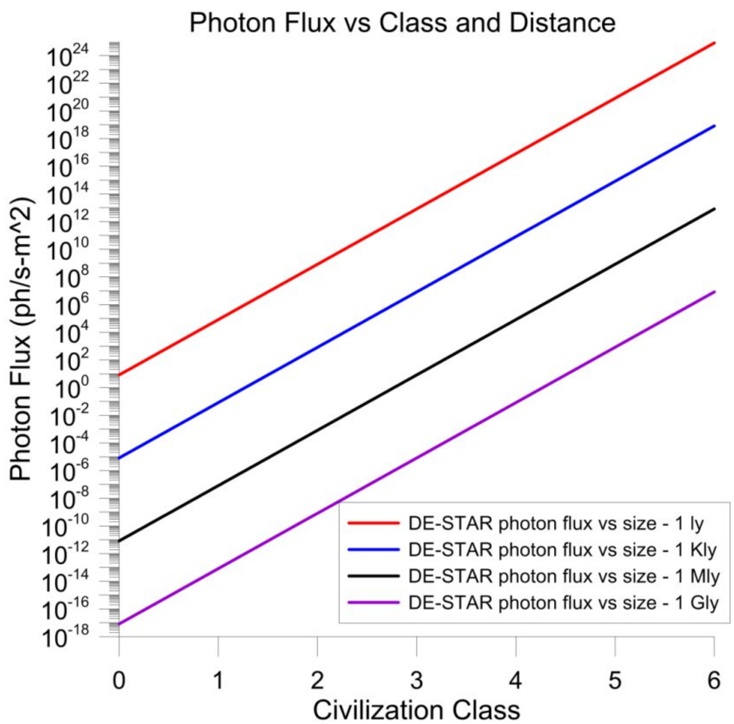

Figure 2 – Photon flux at Earth vs. civilization class and distance. Distances are luminosity distance. See below for cosmological effects at higher redshift.

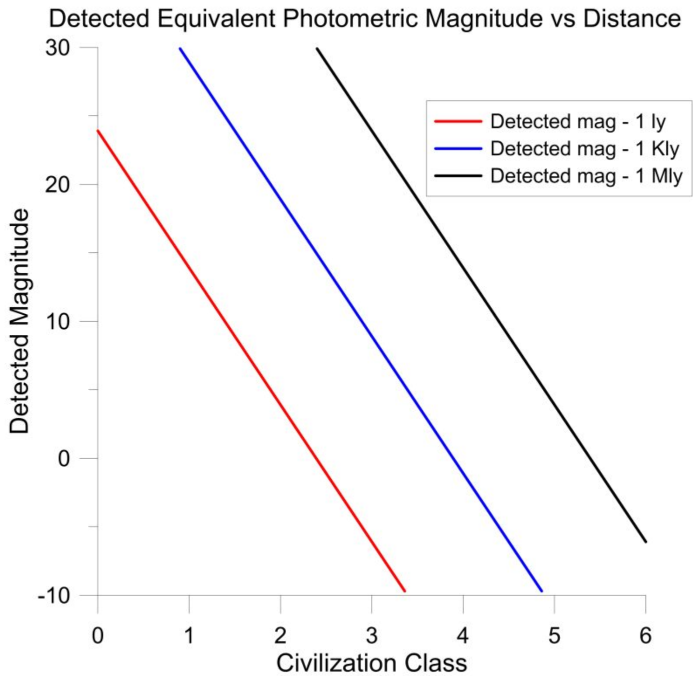

Figure 3 – Equivalent photometric magnitude vs. civilization class and luminosity distance. At distances small compared to cosmological scales the Euclidean distance and luminosity distance are equivalent. The equivalent photometric magnitude is based on an equivalent R~ 4 photometric filter band.

3. FUNDAMENTAL BACKGROUNDS

3.1 Backgrounds relevant for detection

In order to determine the signal to noise of the return signature it is necessary to understand the non-signal related sources of photons. This is generically referred to as the background. There are a number of such backgrounds that are important. Going outward from the detector to the target and beyond, there is:

- Dark current and "readout noise" associated with the detector
- Thermally generated photons in the optical system, under the assumption that the optical system is mostly running near 300 K.
- Photon statistics of the received signal.
- Atmospheric emission – sky glow if the observations are inside the Earth's atmosphere.
- Solar system dust that both scatters sunlight and emits from its thermal signature. Dust in the solar system is typically at a temperature of about 200 K. This is generically called Zodiacal scattering and emission, respectively, or simply Zodiacal light. This assumes a mission inside the solar system. We assume that there is a similar level of equivalent dust in the host civilization "solar system"
- Distant background stars that are in the field of view
- Sunlight scattered into the field of view for targets that are near to the sun in the field of view. This is generally only important for targets that are very close to the sun along the line of sight, though off axis response of the optical system can be an issue as well.
- Scattered galactic light from dust and gas in our galaxy.

- The far IR background of the universe, known as the Cosmic Infrared Background or CIB. This is the total sum of all galaxies (both seen and unseen) in the field of view in the laser band.
- The Cosmic Background Radiation or remnant radiation from the early universe. This is negligible for short wavelengths.

In all of these cases the fact that the laser linewidth (bandwidth) is extremely narrow (from kHz to GHz depending on the laser design) and the field of view is extremely narrow, mitigates these effects which would otherwise be overwhelming for a broadband photometric band survey. Heterodyning is also possible could be used in the future but is not assumed as we do not possess large focal plane arrays of such detectors.

Probability of detection of a civilization – Assume there is **one transmitting civilization** S_t in the universe and **one detecting civilization** S_r. We can compute the probability of detection by the receiving civilization. In order to have a detection the signal must arrive after the receiving civilization has evolved to the point of being able to detect the signal. We assume the detecting civilization is at luminosity distance L from the transmitting civilization and thus the probability of detection is the same as the fraction of sky covered by the transmitting civilization assuming a random distribution for the transmitting and receiving civilizations. However, the receiving civilization needs to be receiving during the time the transmitting civilization transmitted beam arrives. If the receiving civilization integrates for longer than the required time to the desired SNR τ then the "probability of detection" is unity IF the receiving civilization is pointed at the transmitting civilization and the transmitting civilization was pointed at the receiving civilization, modulo the time of flight. The actual probability of detection $\varepsilon_{prob\text{-}det}$ assuming the transmitting civilization is "on – i.e., the signal could have arrived" during the time the receiving civilization is receiving AND the SNR condition is met is then:

$$\varepsilon_{prob\text{-}det} = f_t{*}f_r = \Omega_t\, \Omega_{rec}/16\pi^2 = (t/\tau)\, \Omega_{rec}\, \Omega_{beam}/16\pi^2 = \Omega_{rec}\, (t/\tau)\, 4\, \lambda^2 10^{-2S}/16\pi^2$$

The probability can exceed unity in this definition which simply means the signal is detected more than once. We need to think about the evolution of both the transmitting and receiving civilizations, since neither is likely to be static. If our civilization is any indication, we have been unable to receive for about a billion years after life evolved and a million years after humans evolved. Recently, we entered an exponential phase of both detection and transmission capability (even if not utilized) with doubling times of under 2 years. This represents a fundamental complexity in analyzing even our own civilization since the time scale of technological evolution is now vastly shorter than "natural time scales" such as the Sun's lifetime (Gyrs) or the time to "start" technological expansion (Myrs for "human" life). While we naturally focus on the present, it is not reasonable given the extremely small fraction this represents. If we even project 100 years into the future at our current pace we will be in a radically different place to receive and transmit. If our current doubling time persists for this 100 years and assuming a 2 year doubling time, the increase in power would be a factor of $2^{50} \sim 10^{15}$ or a civilization class change of $\Delta S \sim 7.5$. While our current construction capability (not the same folding time as photonic and electronic capability) may limit us currently, this too could change. Such an enormous civilization change would rapidly push us to ponder other limits such as the power of a star to drive a system and thus other saturation effects will no doubt evolve as our technology evolves.

Intelligent Targeting and Filling Factors – Based on our limited (to one) knowledge of life it makes sense, IF we were the civilization transmitting, to target individual "high value" targets such as individual stellar systems or galaxies rather than "empty space". For example, in our galaxy there are approximately 10^{11} stars. Until we know more about the probability distribution of likely stellar candidates we could simply target individual stars and stellar systems instead of just uniformly spreading the transmission time. The covering fraction of "solar systems" cross sections is extremely small compared to the total galactic cross section. We will assume 1 AU for a solar system radius to start (we can scale from there).A simple estimate of the "solar systems" cross section is (number of stars)* (area of solar system). The covering fraction is ~ "solar systems" cross section/(diameter galaxy)^2 . The covering fraction then is ~ 10^{11} (# stars in our galaxy) x ($3\text{x}10^{11}$ m (diam Earth orbit))^2 /(10^5 (ly) x 10^{16} m/ly)^2 ~ 10^{-8} . Even if we expand a planetary radius to 10 AU (~ Saturn) the covering fraction is still only ~ 10^{-6} though we expect the typical "habitable zone" to be smaller than 10 AU. Ideally we would target individual planets (assuming this is where life exists) IF we knew where the planets were AND where to point so they transmitted signal were to intercept the planets upon arrival (we would need to understand the galactic ephemeris and gravitational lensing). As an example, a Class 4 system has a beam size of about $4.5\text{x}10^{-20}$ st or about $2.8\text{x}10^{20}$ beams (gain) on the sphere (4π). As we have 10^{11} stars and more than 10^{20} beams we can gain a factor of more than 10^9 (=$2.8\text{x}10^{20}$ beams/10^{11} stars) by using intelligent targeting of the stars rather than the "empty space" in between. This, of course, assumed we would only target stars in our galaxy and not the distant galaxies beyond which may well be in this “empty space” between the stars in our galaxy. Similarly, a Class 3 civilization has about 2.8×10^{18} beams and we can gain a factor of more than 10^7 (=2.8×10^{18} beams/10^{11}), while a Class 2 civilization has about 2.8×10^{16} beams and we can gain a factor of more than 10^5 (=2.8×10^{16} beams/10^{11}). **This makes a dramatic difference in the probability of detection as shown.** IF the transmitting civilization has knowledge of the planets around distant stars then the “intelligent targeting gain factor” is roughly correct. To understand this more we must consider the beam size at the distant system. For example, the fully synthesized beam for a Class 4 system is about 2×10^{-10} rad. At the “edge” of our galaxy (~ 10^5 ly) this corresponds to a spot size of about 10^{11} m. This is about 1 AU or far larger than any known planet but smaller than our solar system. A Class 3 system has a beam 10 times larger or about 10 AU at the “edge” galaxy. It is important to consider the “filing factor” of the distant solar systems IF the transmitting civilization lacks detailed knowledge about the planets and their orbits. In this case the best approach would be to “raster scan” the “stellar system” out to a “reasonable distance” away from the star in order to intercept high value (possible) planets. This might be 1-10 AU for example, depending on knowledge of the stellar class and likely “habitable zones”.

Simple Beacon and Search Strategies – If another civilization adopts this “intelligent targeting” strategy and leaves the beacon on long enough we can **show that such searches have unity probability of detecting even a single comparably advanced civilization anywhere in our galaxy within a relatively short search time (few years).** Our galaxy is about 0.03 Mpc is “diameter”. This assumes that civilization is beaconing at a wavelength we can detect and that civilization left the beacon on long enough for the light to reach us now. In this blind beacon and blind search strategy the civilization does not need to know where we are nor do we need to know where they are. The civilization must understand the galactic ephemeris, in particular transverse or proper motion and understand some reasonable level of gravitational deflection and lensing in the galaxy. This same basic strategy can be extended to extragalactic distances. In figures 4-8 we show some simple ground based searches using very modest assets using optical systems from 1 mm to 1 m. As seen even extremely small optical systems are can detect civilizations at vast distance. The key issue is that the civilization must understand the concept of “intelligent targeting” to optimize detection.

Nearby Extragalactic Survey – There are 127 galaxies within about 12 Mly of the Earth. Among these are a number of large galaxies including Andromeda (M31) which being the closest (large galaxy) is about 2.5 Mly away. Andromeda contains approximately one trillion stars or at least 2-4 times the number of stars as our galaxy. A class 4 civilization on Andromeda has an equivalent photometric magnitude of approximately $m_v = 17$. This is easily detectable in a small (20 cm diameter) consumer telescope with a low cost camera integrating for less than 100 seconds. The dominant stellar population of Andromeda has an angular size of about 2-3 degrees. This is a convenient size that can be surveyed with either a wide field telescope or a raster scan of narrowed images. In a single 1 square degree image of the core region of Andromeda we could survey more than 100 billion stars in a single image and thus close to that many exoplanets, assuming Andromeda has a similar distribution of exoplanets as we have seen in our own galaxy with Kepler. This is clearly an extraordinarily rich target. While the average distance to these stars is about 25 times further than the distant stars in our own galaxy and thus will have a smaller flux by the square of the distance from the same civilization class, the ability to observe this large number of potential exoplanets in one image gives a unique SETI opportunity. Quantitatively it takes less than 1 ms of exposure to the class 4 civilization beam in a 1 m telescope on the Earth to achieve an SNR=10 (Fig 26). **If a class 4 civilization in Andromeda wanted to target the Milky Way and used our “intelligent targeting” scheme to maximize detection by intelligent life on planets, such as ourselves (ie target the stars in the Milky Way), then a simple Earth based 3 year survey with a 1 meter telescope would detect a single class 4 civilization anywhere in Andromeda with near unity probability.** This is also essentially what is shown in Fig 8. This assumes the Andromeda civilization is transmitting long enough for us to technologically evolve to the point where we would indeed mount a search to search for “them” and that we were receiving on a wavelength they were transmitting on. This also requires that the civilization has a detailed knowledge of our galaxy’s stellar motions in order to predict where the Milky Way stars and hence planets are when the signal arrives. A class 4 beam is about 0.2 nrad for $\lambda = 1\mu$m and at 2.5 Mly (ie spot size in the Milky Way from Andromeda) has a spot size of 5×10^{12} m or about 33 AU. This is well matched to a solar system size. At present we do not possess the technology to predict the position of stars with this precision so this remains a question as to whether more advanced civilization would have this capability.

The SNR is relatively independent on our effective spectroscopic detection resolution and the same statement (near unity probability of detection) is true for R = 1 and R = 1000 modulo issues such as OH emission lines which depend on the wavelength being detected. A simple search strategy uses fixed bandpass filters with a possible multichroic splitter, among other schemes.

In addition to Andromeda there are also many other nearby galaxies with similarly target rich environments though the increasing distances decrease the probability of detection for a given civilization class and a given Earth based observing asset. There are other smaller nearby galaxies that are closer than Andromeda as well.

Detection Probability – Below we show a series of cases for galactic and a nearby extragalactic survey. We choose two filter types. Figure 4 uses a 1 nm filter and figures 5-8 use a 1 µm wide filter. A 1 nm filter is a state of the art interference filter while a 1 µm "filter" means essentially no filter. WE show the 1 µm wide filter case to show the relative independence of the detection probability with filter bandwidth. However it is important to understand the non-thermal sources of emission in our atmosphere such as OH emission in the near IR, particular for J (1.1-1.4 µm) and H (1.5-1.8 µm) bands. OH emission occurs in the upper atmosphere and is highly variable (both spatially and temporally). It is important to block these bands if possible in ground based surveys. The SNR and detection probability assumes these lines are blocked. This is discussed much more fully in the paper given in the acknowledgements. A space base survey would avoid this and other non-thermal atmospheric emission lines.

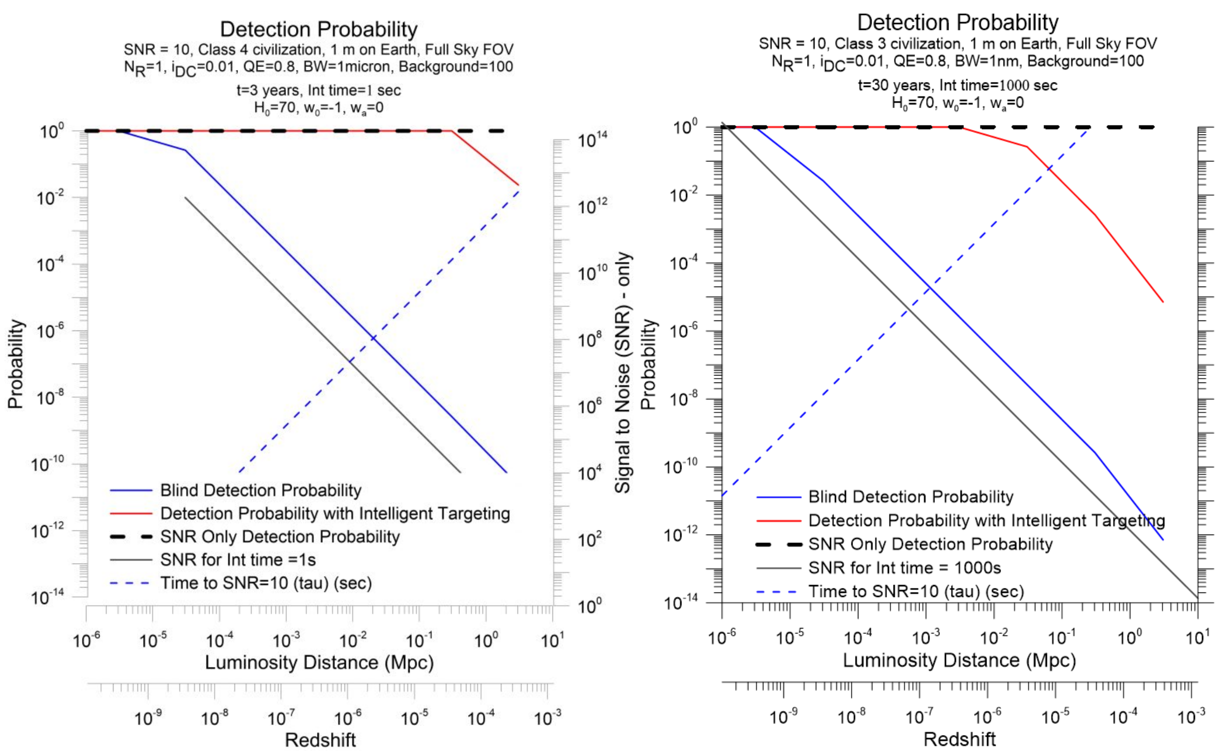

Figure 4 – Left: Probability of detection vs luminosity distance and redshift for a modest 1m ground based wide field survey that observes the full sky all the time for 30 years with an integration time of 1000 s per image and filter BW=1nm (narrow band). The transmitting civilization is Class 4. Three types of detection probability are shown. One is based only on achieving the SNR (10 here) for a single integration time and assumes the Earth based system views the transmitter beam. The second (blue) is a blind survey of a SINGLE civilization that randomly (or uniformly) scans the sky during a 30 year Earth observing campaign. As can be seen the blind survey could easily detect the civilization if it were pointing at the Earth. The third (red) is computed assuming "intelligent targeting" is used where known stars "habitable zones" are targeted, using the "gain factor" discussed, rather than simply a uniform scan. Note that in this case the probability of detection increases dramatically. The SNR (dark grey) for integration time = 1000 s is also shown and uses the right-hand Y axis. The integration time to SNR = 10 (blue dashed) is also shown – use left-hand Y axis. A benchmark or concordance model is used for the cosmological relationship between luminosity distance and redshift. **Right**: Same but for a class 3 civilization.

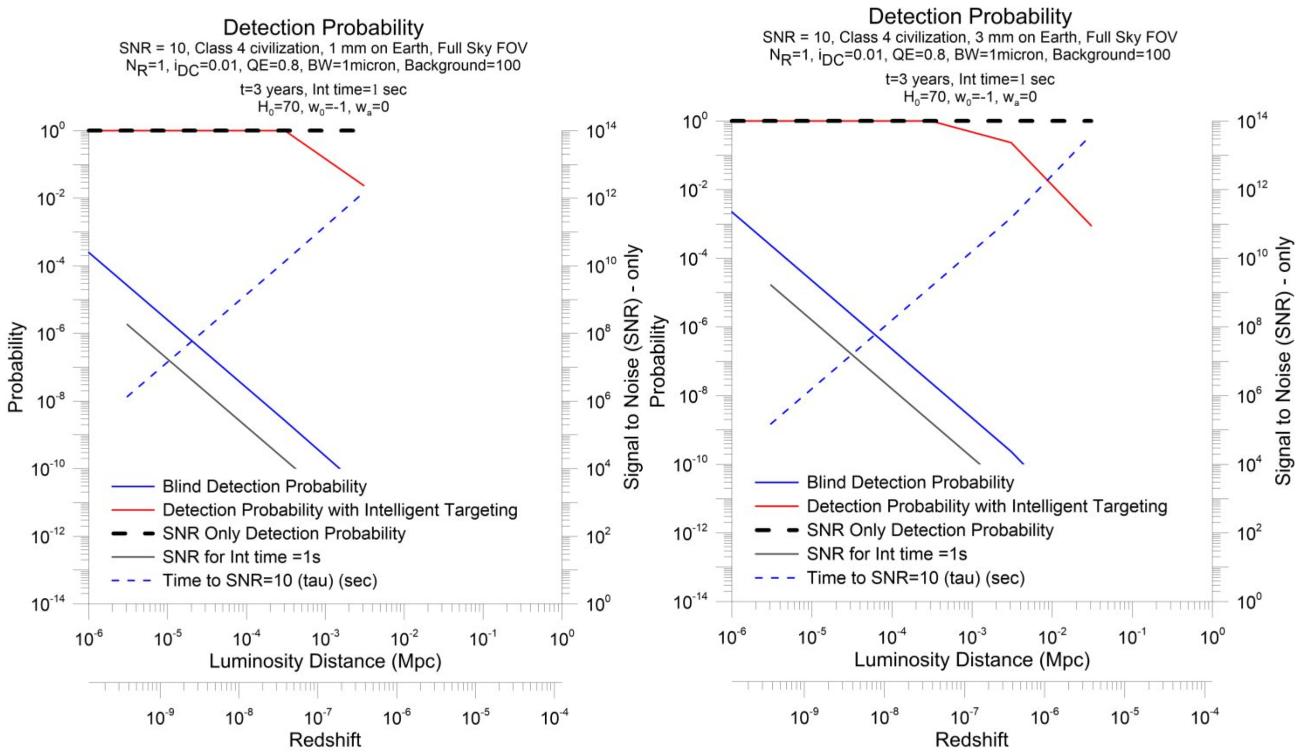

Figure 5 – **Left:** Probability of detection vs luminosity distance and redshift for a 1mm optical aperture ground based wide field survey that observes the full sky all the time with an integration time of 1 s per image and filter BW = 1 µm (essentially "wide open") for 3 years. The transmitting civilization is Class 4. The SNR (dark grey) for integration time = 1 s is also shown and uses the right-hand Y axis. The integration time to SNR = 10 (blue dashed) is also shown – use left-hand Y axis. With intelligent targeting of stellar systems even a millimeter size optic, like that in a cell phone, with a high performance detector full sky survey will detect a class 4 civilization out to significant distances in the galaxy assuming that the civilization randomly beacons and uses the intelligent targeting strategy as discussed in the text. **Right:** Same for 3 mm. Note that the Intelligent Targeting probability of detection is relatively independent of integration time. 1 second is chosen for convenience.

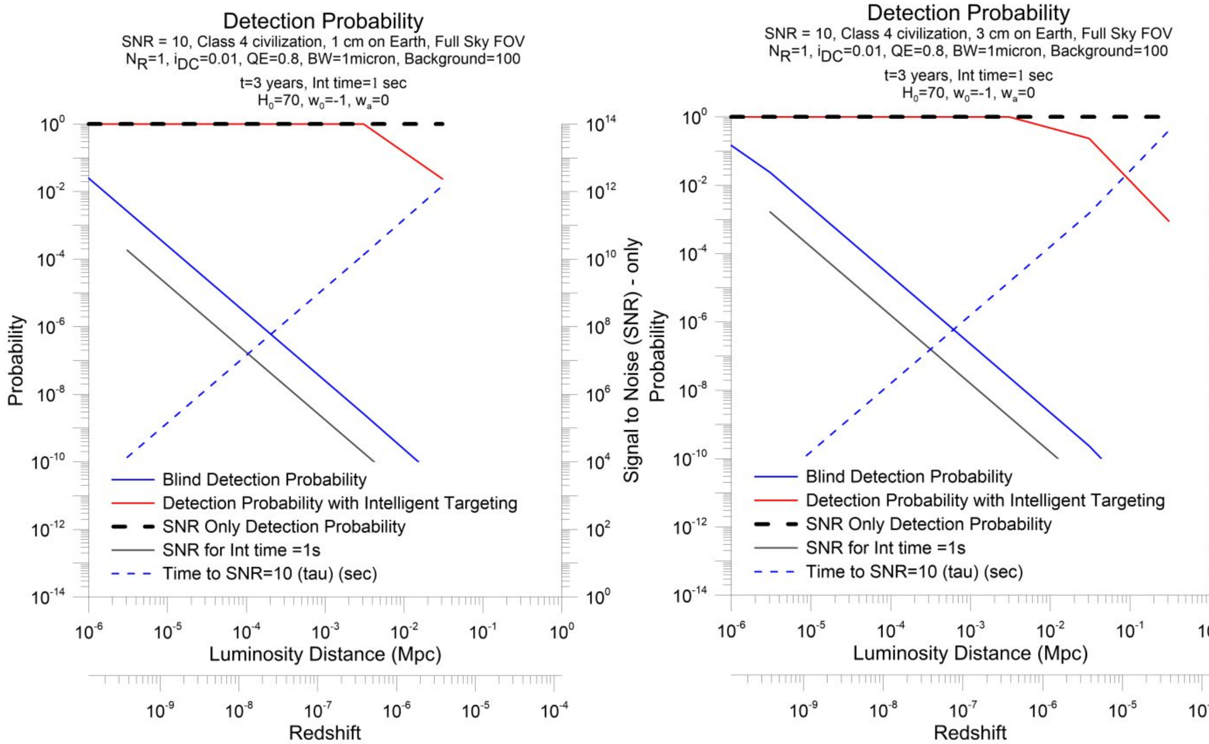

Figure 6 - **Left:** Probability of detection vs luminosity distance and redshift for a 1cm optical aperture ground based wide field survey that observes the full sky all the time with an integration time of 1 s per image and filter BW=1μm (essentially "wide open") for 3 years. The transmitting civilization is Class 4. The SNR (dark grey) for integration time = 1 s is also shown and uses the right-hand Y axis. The integration time to SNR = 10 (blue dashed) is also shown – use left-hand Y axis. With intelligent targeting of stellar systems even a centimeter class optics full sky survey will detect a class 4 civilization out to large distances in the galaxy assuming that the civilization randomly beacons and uses the intelligent targeting strategy as discussed in the text. **Right:** Same for 3 cm. Note that the Intelligent Targeting probability of detection is relatively independent of integration time. 1 second is chosen for convenience.

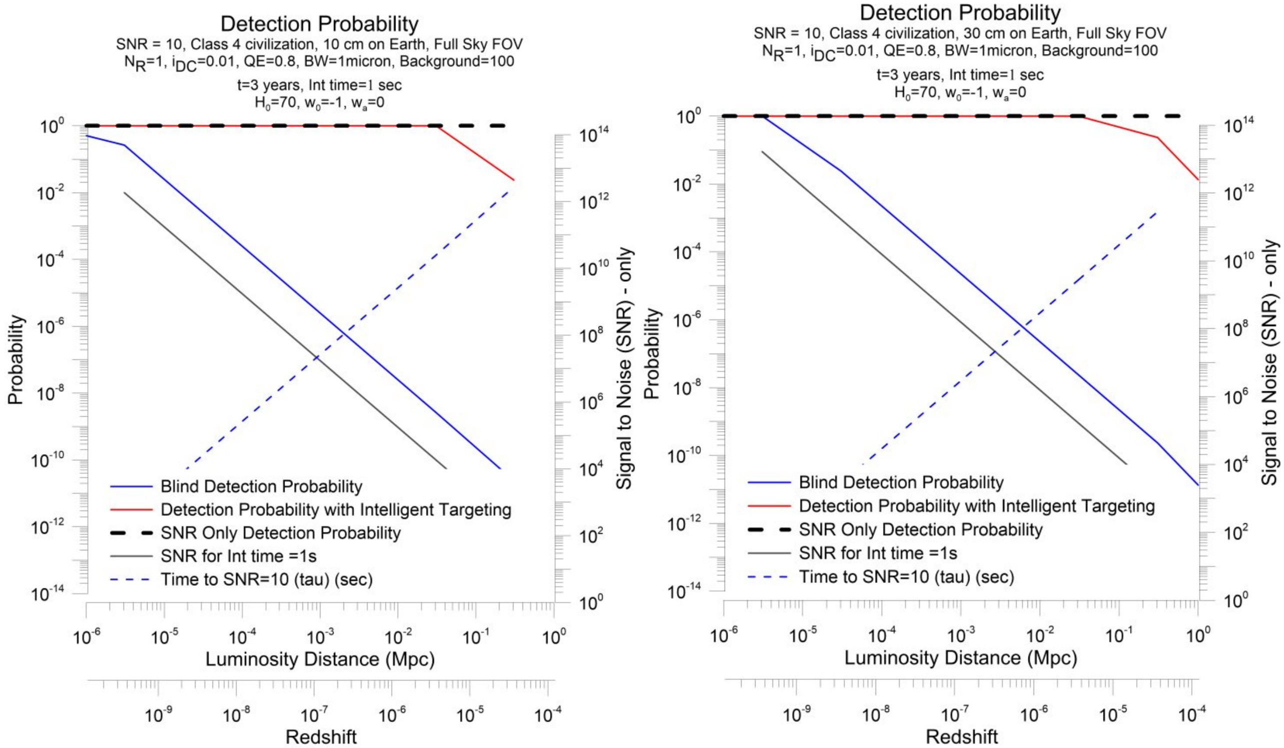

Figure 7 – **Left:** Probability of detection vs luminosity distance and redshift for a 10 cm optical aperture ground based wide field survey that observes the full sky all the time with an integration time of 1 s per image and filter BW=1μm (essentially "wide open") for 3 years. The transmitting civilization is Class 4. The SNR (dark grey) for integration time = 1 s is also shown and uses the right-hand Y axis. The integration time to SNR=10 (blue dashed) is also shown – use left-hand Y axis. With intelligent targeting of stellar systems even a 0.1 and 0.3 m full sky survey will detect a class 4 civilization anywhere in the galaxy assuming that the civilization randomly beacons and uses the intelligent targeting strategy as discussed in the text. **Right:** Same for 30 cm. Note that the Intelligent Targeting probability of detection is relatively independent of integration time. 1 second is chosen for convenience.

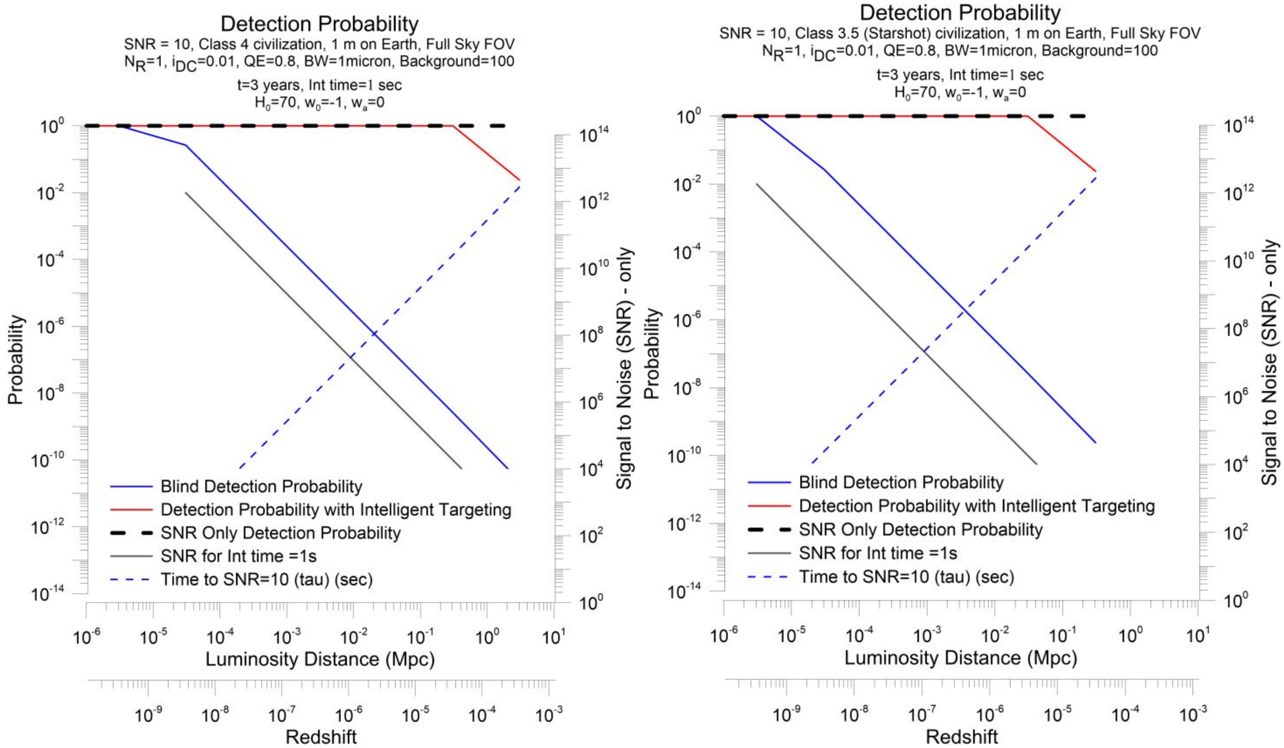

Figure 8 – **Left:** Probability of detection vs luminosity distance and redshift for a 1m optical aperture ground based wide field survey that observes the full sky all the time with an integration time of 1 s per image and filter BW=1μm (essentially "wide open") for 3 years. The transmitting civilization is Class 4. The SNR (dark grey) for integration time = 1 s is also shown and uses the right-hand Y axis. The integration time to SNR=10 (blue dashed) is also shown – use left-hand Y axis. With intelligent targeting of stellar systems, a 1 m full sky survey will detect a class 4 civilization anywhere in the galaxy and in Andromeda assuming that the civilization randomly beacons and uses the intelligent targeting strategy as discussed in the text. **Right:** Same for a class 3.5 civilization which is about the equivalent of a 100 GW 1 km array as the proposed Starshot array might be. Note that the Intelligent Targeting probability of detection is relatively independent of integration time. 1 second is chosen for convenience.

4. CONCLUSIONS

Given our developments in directed energy systems we have now reached the point in human technological evolution to project our own presence across the entire universe if we chose to do so. We are on an exponential growth phase in this technology. Even modest systems appear as the brightest objects (in terms of SED) in the universe within a narrow linewidth. We have outlined logical search strategies that search for signatures of an exceeding large number of candidates extending to cosmological scales, including searches at high redshift, that can help us search for the answer to the question of "are we alone". This can be done with very modest resource allocations.

ACKNOWLEDGEMENTS

We gratefully acknowledge funding from the NASA California Space Grant NASA NNX10AT93H in support of this research and NASA NIAC 2015 NNX15AL91 as and from the Emmett and Gladys W. Fund. Portions of this paper come from a much more complete paper: **The Search for Directed Intelligence"** http://arxiv.org/abs/1604.02108