Active Galactic Nuclei (AGN)

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Abstract. AGN dominate the extragalactic background at both ends of the electromagnetic spectrum, from 10MHz in the radio to 100 keV x-rays. They are likely to be the most important source of ionizing photons since the big bang. Yet we do not have a profound understanding of how and when supermassive black holes form, how the energy of the relativistic potential wells is released, and if the spin energy of black holes is uniquely responsible for powerful radio sources. We propose a hierarchy of surveys using the unique *etendue* of Pan-STARRS to take a full census of the AGN zoo to study the formation and evolution of AGN and their intimate relationship with the dynamical and stellar evolution of their host galaxies and environments. The AGN discovered and monitored by these surveys will probe several major transitions in the life of the universe: the epoch of reionization, the epoch of metal formation in the IGM, the epoch of spheroid formation, the epoch of peak AGN activity, and the subsequent decline of AGN to a population of dark remants in the centers of most galaxies today.

We need a total of 3.7 Pan STARRS Years for the science described in this proposal.

1 Introduction

The enormous dynamic range of intrinsic AGN luminosities ($> 10^6$) requires a hierarchy of surveys:

- a wide area single-band synoptic survey for variable sources ($> \pi$ steradians),
- a wide multi-color ($grizY$) survey ($> \pi$ steradians),
- a medium deep multi-color ($grizY$) survey (1200 square degrees),
- a confusion limited ultra-deep multi-color ($grizY$) survey, to the limit of uncorrected ground based observing (28 square degrees).

This approach will provide a unique census of active nuclei in the universe and establish the taxonomy of the zoo of AGN from the most underluminous advection-dominated accretion nuclei in nearby galaxies to the brightest quasars and faintest radio galaxies at redshifts of $z \sim 7$. This approach will also provide the best possible match for cross comparisons with all-sky and deep targeted surveys at other wavelengths. The multi-survey approach is ideal for maximizing the scientific return of the *etendue* and time resolution that are unique to PanSTARRS.

2 Scientific Questions

- What is the redshift cut-off for quasars?

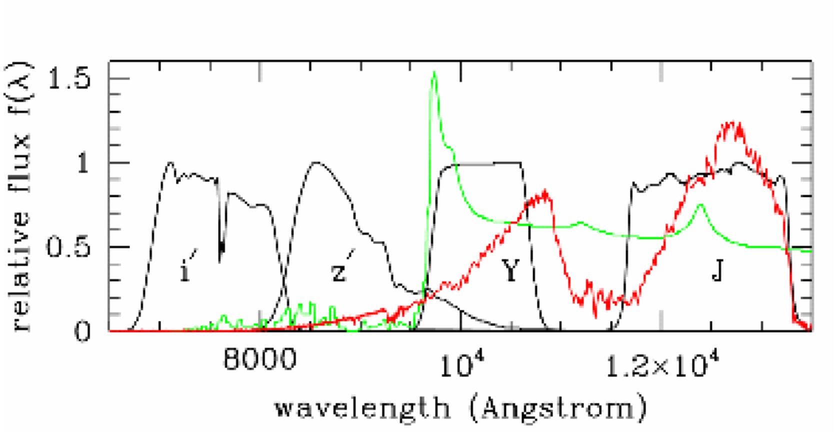

Fig. 1. Illustration of drop-out method for finding $z = 7$ quasars. using a Y band filter. The green line shows a model spectrum of quasar redshifted to $z = 7$. The red line shows the spectrum of the T dwarf SDSS1624 (Leggett et al. 2000a,b). Filter transmission curves are printed in black. Between Y and J is a region of strong telluric atmospheric absorption. From Lawerence et al. 2001.

Using I band drop-outs, the Sloan Digitial Sky Survey (SDSS) has discovered the most distant objects the universe, quasars up to redshifts $z = 6.4$ (Fan et al 2002). This must be near the limit of the SDSS since at this redshift the Lyman break has nearly left the z' band. In the 10,000 square degrees of a Pan-STARRS $b > 30\,$deg survey we can expect 25 very bright quasars ($M_{1450} < -26.8$) for $5.8 < z < 7.2$ if the power-law luminosity function of Fan et al. 2001 can be extrapolated to those redshifts. Figure 3 shows how the rare high redshift quasars can be distinquished from the wealth of main sequence and L and T dwarf stars in a $(i - z)$ vs. $(z - Y)$ color-color plot. The density of lower luminosity quasars at $z > 5$ is unknown, but a Pan-STARRS wide area survey will reach nearly 2 magnitudes deeper into the quasar luminosity function than UKIDSS (limit $Y = 20.5$). If quasars exist up to and beyond $z = 7$, Pan-STARRS will find them. (A figure of $(i - z)$ vs. $(z - Y)$ color-color plot to demonstrate selection between high redshifts quasars and T-dwarfs will be sent by Steve Warren.)

- When did the universe become reionized?
  The epoch of hydrogen reionization is one of the outstanding unknowns in cosmology. Establishing it will give clues to the origin of structure and the sources of the first ionizing photons since the big bang. Discovery of bright quasars to $z < 7.2$ will enable the Gunn-Peterson test of a neutral IGM to these redshifts. Spectra of the bright quasars found with Pan-STARRS will establish the metallicity, and degree of stellar enrichment of the IGM to the earliest epochs. (e.g Songaila & Cowie 2002).

- What is the origin of metal contamination in the diffuse IGM?
  Metal absorption lines in high luminosity high redshift quasars demonstrate a ubiquitous metal contamination of the IGM (Cowie et al 1995). Did these metals come from feedback mechanisms of ejection or stripping (e.g. Gnedin & Ostriker 1997, Madau, Ferrara & Rees 2001) or in a diffuse Population III at very high redshift (e.g. Carr et al. 1984, Abel et al. 1998)? An apparent baseline metallicity of $[Fe/H] \sim 3$ in damped Lyman alpha systems (Prochaska, Gawiser & Wolfe 2001) which is similar to that of low metalicity stars in the Galactic halo, is best fit by a model with a first generation of Pop III very massive stars. With the Y band, PanSTARRS will be able to find higher redshift quasars than SDSS, up to $z \sim 7$ alone, and as far as $z = 7.8$ in conjuction with IR surveys of smaller area. Extending to the highest redshifts is of crucial importance to understanding the formation of galaxies.

- What is the epoch of spheroid formation and how does it relate to first generation of AGN?
  In monolithic models of spheroid formation a single burst of star-formation is followed largely by passive stellar evolution. This view has found support by identifying the hosts of radio sources as high redshift ellipticals (e.g. Dunlop et al. 1996) as well as other indications from the small scatter in color-magnitude relations in clusters at $z \sim 0.5$ suggesting the bulk of star formation occured at $z > 3$ (Ellis et al. 1997). In hierarchical models the assembly of giant ellipticals occurs from the merging of intermediate mass disks at lower redshifts (e.g. Kauffmann & Charlot 1998). Thus the formation epoch of massive ellipticals is still a major unanswered question. In both pictures one expects the most luminous AGN to be within the most massive galaxies. Finding the most distant AGNs is one way of finding the earliest signs of galaxy formation. The highest redshift optically-selected quasars from the SDSS reach out to $z \sim 6.4$. whereas the highest known redshift radio galaxies known to date have only $z = 5.2$. (See Figure 3.) The fact that optically selected quasars are found at higher redshifts than radio galaxies may be a physically significant clue to the formation of AGN, or it may be a selection effect due to the comparative difficulty of identifying and obtaining spectra of the vastly fainter radio galaxies. The identification of galaxies and quasars at optical wavelengths is by necessity biased towards the bluest, most ultra-violet active systems – such selection can not detect obscured or highly reddened systems. Radio source selection provides a means of pinpointing massive galaxies irrespective of extinction. To find the highest redshift radio sources requires pushing to the faintest limits we can reach from the ground: the confusion limit at $r \sim 29$. An ultra-deep survey to the confusion limit, which can detect L_* galaxies irrespective of their apparent AGN luminosity, will enable the detection of an unobscured radio galaxy out to $z \sim 7$, and pinpoint (by elimination) any remaining population of extremely high redshift or dust-enshrouded sources.

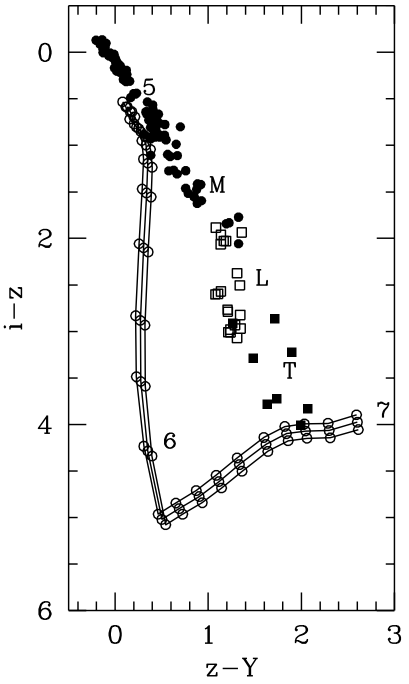

Fig. 2. Two color *izY* diagram showing colors of main-sequence stars (filled circles), and L and T dwarfs (open and filled squares) (Vega magnitudes). The chains show model quasar colors $5 < z < 7$, $\Delta z = 0.1$ with three different continuum slopes. For $5.4 < z < 6.7$ and $z > 6.8$ these colors are very effective for isolating high z quasars. For $z \sim 6.7$ the quasars will overlap with the very end of the T-dwarf sequence. Courtesy of Steve Warren.

- What is the nature of extragalactic radio sources and how is their evolution different from optically selected quasars?
  Remarkably, the evolution of the radio luminosity function (RLF) is still poorly known. The sad state of affairs is shown in Figure 4 from Waddington et al. 2001., as compared with the optical luminosity function from Fan et al. 2001 (Figure 5). The Leiden Berkeley Deep Survey (LBDS) suggests a significant decrease in the number of low-power radio sources beyond a redshift of one (Waddington et al. 2000, 2001), unlike anything seen in the optical quasars LF (e.g. Fan et al. 2001a, 2001b.). This may be due to the difficulty of identifying radio sources; some sources in the LBDS could be improperly identified with foreground galaxies, or the evolution of radio

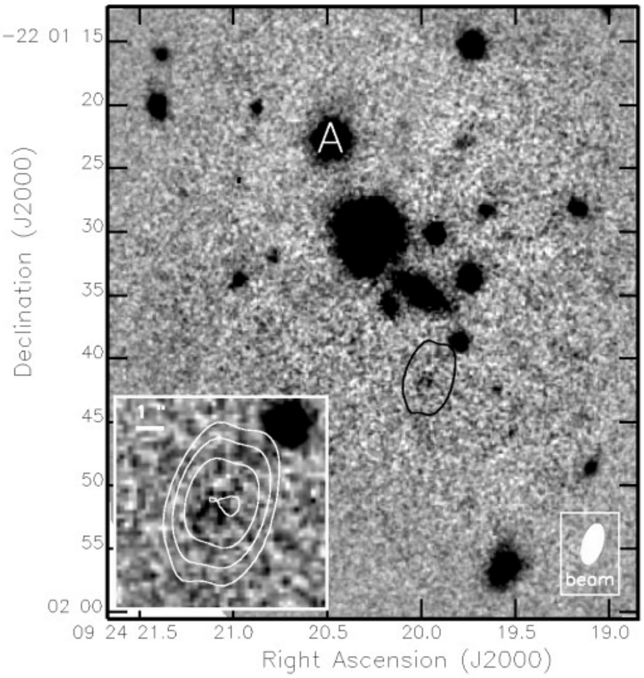

Fig. 3. Keck image of a radio galaxy at $z = 5.19$ from van Breugel et al. 1999. The identification is the very faint object surrounded by the VLA radio map contours.

source AGN could be intrinsically very different. However the real RLF is not a one-dimensional function of luminosity (e.g. Blundell et al 1999). Individual radio sources age rapidly and change in size, luminosity, and radio spectrum as they grow outwards from the nucleus. The diversity of radio source types, from classical doubles of type FRI and FRII to compact steep spectrum sources (CSS), Gigahertz peakers, and flat spectrum cores reflect the diversity of the population as a whole, and in some cases perhaps the evolution of individual sources as they are born, grow, and ultimately die out. Confused with this are effects of beaming, orientation, and unification. For example, steep spectrum QSRs appear to be unified with FRII radio galaxies (Barthel 1989) and blazars with FRIs (Urry & Padovani 1995, Antonucci 1993), at high luminosity, but at lower luminosities the situation is much less clear.

The only way to disentangle these effects is with large complete samples of radio sources with identifications and redshifts. Spectroscopic redshifts of such large samples of very faint objects are impractical, but five band photometric redshifts can have accuracies of $\Delta z = 0.2$.

The SDSS however will only identify 30 percent of the VLA FIRST radio sources because the majority of these sources are simply too faint (Ivezic et al. 2002). In comparison, a PanSTARRS wide field multi-color survey will identify 90 percent of the FIRST survey. The medium deep survey will obtain perhaps 98% percent completeness. Of course the remaining very red and/or very distant sources are the most interesting. The ultra-deep will potentially approach 100 percent completeness of a sample of $\sim$ 3000 sources and clearly pinpoint any remaining extremely high redshift or extremely obscured sources.

- How does the extraordinary dichotomy between radio-loud AGN and radio-quiet AGN arise, and what is its relation to the development of the Hubble sequence? Does this dichotomy arise from the spin angular momentum of the super massive black holes, and are the statistics consistent with the spin-up of massive black holes and subsequent efficient extraction of the rotational energy of black holes? What is the degree of unification in radio-loud sources (QSR vs. radio galaxies) and how does it depend on luminosity, age, and redshift? What is the degree of unification in radio-quiet sources (Seyfert I vs. Seyfert II radio galaxies) how do bright quasars and broad-absorption line quasars fit into this scheme as a function of luminosity, age, and redshift? Photometric redshifts and multi-dimensional luminosity functions of large samples of radio, far infrared, x-ray, (and even gamma-ray) selected objects will enable the statistical disentanglement of these populations to investigate the fueling, lifecycle, and demise of AGN and its relationship with the dynamical and stellar evolution of the host galaxies.

- What are the masses of black holes in AGN, and how do they depend on the properties of the host galaxy? In nearby galaxies, the central black holes can be measured by stellar kinematic techniques and by masers. However to build up a statistically significant sample of black hole mass measurements will require reverberation mapping of a significant number of AGN undergoing outbursts. When an outburst is detected by the PanSTARRS variability program follow up spectroscopy of the size and structure of the Broad Line Region can be obtained by measuring timed delay response of the emission line region to variation in continuum emission, and result in a measure of the mass of the black hole (Peterson 1993, Korista et al. 1995, Wanders et al. 1995). Measurements of black hole mass can then be compared with host galaxy velocity dispersions (See Figure 6) as well as other properties, including radio power and measures of orientation. The time delayed response of the near infrared continuum can also probe the outer regions of accretion tori and conditions of the circum-nuclear region. High resolution spectroscopy may allow us to relate distinct AGN outbursts with specific physical events such as tidal disruption and accretion of stars or global instabilities in the accretion disk, or even the very rare merger of black holes.

3 Survey Requirements

To satisfy the goal of a census of the AGN population over an intrinsic luminosity range of 10^6, a hierarchical set of surveys is ideal:

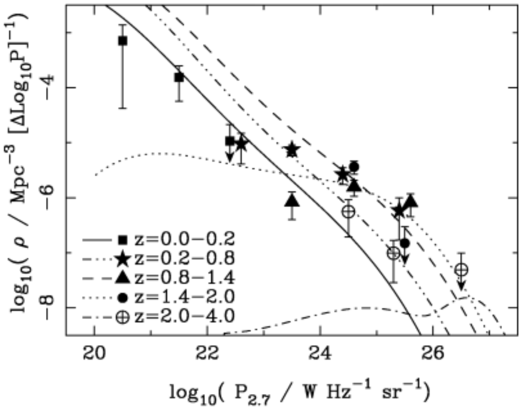

Fig. 4. The state of the art of the Radio Luminosity Function as determined from the decade long Leiden-Berkeley Deep Survey (LBDS), from Waddington et al. 2001. Note the peculiar flattening at $z > 1$. If the absence of moderate to low-power AGN radio sources at $z > 2$ is real it suggests a very different evolution scenario for radio-loud than radio-quiet AGN.

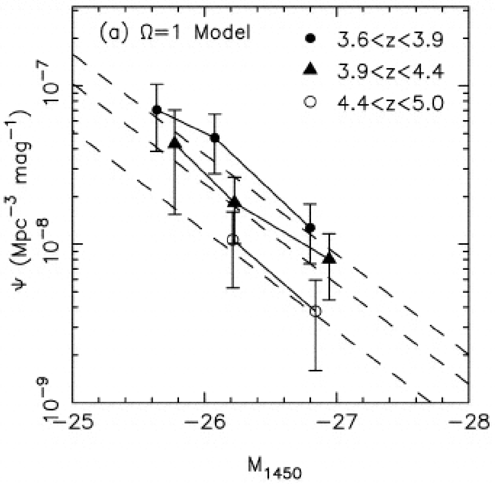

Fig. 5. The optical quasar luminosity function from the SDSS, Fan et al. 2001. Note the evolution is consistent with a more or less constant offset in luminosity and/or number evolution.

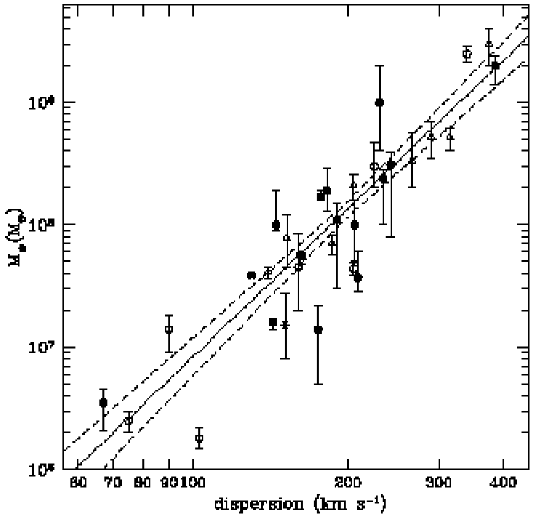

FIG. 7.—Data on black hole masses and dispersions for the galaxies in Table 1, along with the best-fit correlation described by eqs. (1) and (19). Mass measurements based on stellar kinematics are denoted by circles, on gas kinematics by triangles, and on maser kinematics by asterisks; Nuker measurements are denoted by filled circles. The dashed lines show the 1 σ limits on the best-fit correlation.

Fig. 6.

- Wide field single-band synoptic search for variable sources ($> \pi$ steradians)
- Wide field multi-color survey ($> \pi$ steradians)
- Medium deep multi-color survey – 1200 square degrees
- Ultra-deep multicolor survey – 28 square degrees

AGN variability studies will be greatly aided by the solar system wide band synoptic survey for identifying outbursts. AGN science places no critical constraint on the details of this survey. For the wide field multi-color survey for AGN, going below Galactic latitude of $b_{II} < 30\,\mathrm{deg}$ is not strictly necessary, and any area coverage $\geq \pi$ steradians above this limit would be satisfactory. Of course we expect this survey to be continued into the Galactic plane for Galactic and stellar science, so we include this in the time estimate.

3.1 Filters

Five filters *grizY* are required for color selection of quasars, photometric redshifts of host galaxies and their companions. The Y band is of particular interest for its unique infrared coverage and ability to extend the survey out to redshifts $z \sim 7$. The best y bandpass to discriminate between high z quasars and T dwarfs is 970-1070 nm (Warren and Hewett 2002). This implies that the z filter, which currently is defined as an open ended RG830 would be replaced with something like a 830-940 nm band pass.

Note that determination of the Y band sensitivity is crucial to many aspects of the extragalactic program. We hope to have quantitative measurements regarding this by August 2003.

3.2 Depth

Assume a single 1.8-m PanSTARRS telescope with a 25% obstruction by the secondary. We estimate 5σ point source AB magnitude sensitivities using

$$S/N = 10^{-0.2(2m-\mu-m_1)} \left(\frac{t}{\pi\omega}\right)^{1/2}$$

where m is the apparent magnitude of the object in a given band, μ is the sky brightness in that band in magnitudes per square arcsecond, m_1 is the magnitude that produces $1e^-$/sec, $\omega = 0.6''$ is FWHM seeing in arcseconds, and t is the integration time in seconds. Observations are assumed to be background limited, i.e. the noise in the sky dominates over any read noise. In reality the sky brightness varies strongly with lunar illumination in the blue and with atmospheric conditions in z and Y, and the value for Y is interpolated between z and J. The CCD response in Y is still to be determined; Tonry has estimated QE from 20 to 40%. Sky surface brightness numbers are calculated from the Subaru web page. The values for m_1 are calculated using the expression from Stoughton et al. (ApJ 128 485) for SDSS and scaling.

Table 1. Assumed AB sensitivities for single 1.8m telescope with 25% obstruction

Filter	nm	m_1(AB)	μ(AB)	5 σ
g	475	24.8	21.4	21.0
r	625	24.8	20.4	20.5
i	772	24.8	20.0	20.3
z	890	23.8	18.8	19.2
Y	1020	21.0	18.0	17.4

For each survey we wish to detect the reddest objects consistent with an evolved stellar population which leads us to the computed limiting magnitudes and exposure times for each survey.

3.3 3 π survey – 30,000 square degrees

Over the course of the 10 year survey, each foot-print of 7 square degrees would reach the following depths with the integration times indicated in Table 1.

Total is 14,300 seconds for one telescope and 7 square degrees. For 30,000 square degrees or 4285 footprints with the full array of four telescopes this will take 1.5×10^7 seconds of integration time. Assuming 10 hours per night this will take 1.2 years worth of good nights.

Table 2. 3π Survey

Filter	nm	mag	seconds	percent time
g	475	25.2	2300	15
r	625	25.0	4000	26
i	772	24.2	1300	10
z	890	22.9	900	11
Y	1020	21.1	5800	38

3.4 Medium deep survey – 1200 square degrees

To detect an evolved stellar population out to redshift of z=1.8 where the 4000 break passes through the Y bandpass. This is a natural redshift to search to.

Table 3. Medium Deep Survey

Filter	nm	mag	seconds	percent time
g	475	27.0	6.5×10^4	15
r	625	26.8	1.1×10^5	26
i	772	26.0	3.7×10^4	10
z	890	24.7	4.0×10^4	11
Y	1020	23.9	1.5×10^5	38

Total is 4.0×10^5 seconds per 7 square degree footprint for one telescope. For 1200 square degrees or 171 foot prints with the full array of four telescopes this will take 1.7×10^7 seconds of integration. Assuming 10 hours per night this will take 1.3 years worth of Pan STARRS years.

3.5 Ultra-deep survey – 28 square degrees

To detect an evolved stellar population out to redshift of $z \sim 3$.

Table 4. Ultra Deep Survey

Filter	nm	mag	seconds	percent time
g	475	29.0	2.5×10^6	15
r	625	28.8	4.3×10^6	26
i	772	28.0	1.5×10^6	10
z	890	26.7	1.6×10^6	11
y	1020	25.9	6.3×10^6	38

Total is 1.6×10^7 seconds of on source integration time per 7 square degree footprint to reach the confusion limit for un-corrected ground based observing with one telesc ope. For four footprints or 28 square degrees, but with an array of four telescopes the total integration time is still 1.6×10^7 seconds. Assuming 10 hours per night this will take 1.2 years worth of Pan STARRS years.

3.6 Wide Band (B+V+R) synoptic wide area survey)

The solar system survey will reach $m_R = 24$ per footprint with a cadence of a few hours and a few days. AGN science can accept whatever specific cadence is adopted for the NEO threat. Variable AGN will appear in this survey (as will all the other all other variable sources). For light curves alone, the ongoing surveys will serve as the followup. More specific follow up is included below.

Outbursts above a threshold (to be determined) can be followed up with spectroscopic observations for reverberation mapping.

3.7 Astrometry

We require only that the astrometry be good enough to reject known variable stars and AGN from the Pan-STARRS database, i.e. 0.5 arcsec.

3.8 Image Quality and Sky Brightness

FWHM = 0.7 arcsec maximum.

3.9 Photometric Accuracy

We cannot accept systematics which will compromise photometry at $\delta m = 0.04$, therefore we require that the photometric zero points be good to at least 0.02 mag.

3.10 Follow Up Strategy

The Ultra-Deep survey would be strongly complemented by deep observations in U band with MEGACAM and in J, H, and K with WIRCAM (CFHT) and WFCAM (UKIRT). We intend to propose such complementary observations to the IfA as an IfA survey.

Follow-up of high z quasars, radio galaxies, and AGN outburts will be by normal means with other large telescopes.

3.11 Relation to Other Surveys

- Radio - FIRST, WNESS, NVSS, 8C, 6C, LOFAR, SKA
- Submillimeter - Plank
- FIR - IRAS, ASTRO-F, SIRTIF-SWIRE
- NIR - 2MASS, UKIDSS
- Optical - SDSS, CFHTLS, DPOSS
- UV - GALEX
- X-rays - Rosat, XMM
- Gamma-rays - SWIFT, GLAST, EXIST, see GRBs above

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