Overview of Wide Field Infrared Galactic Surveys

Lynne A. Hillenbrand (Caltech)

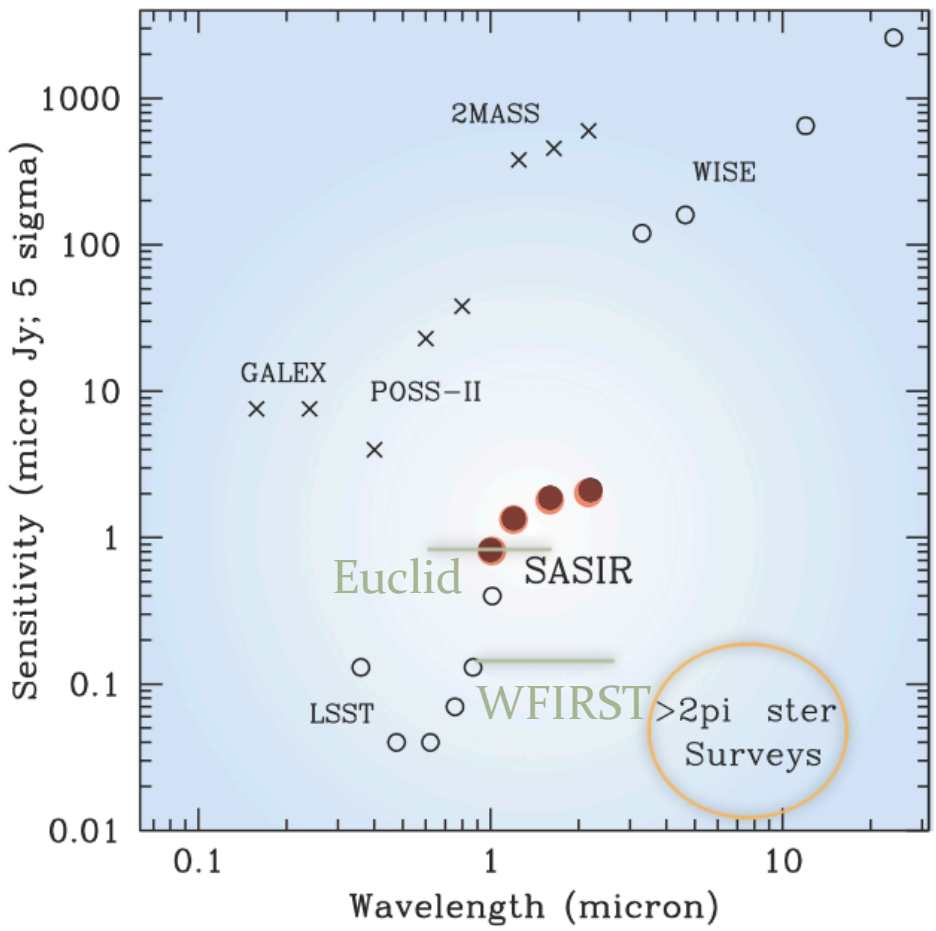
[with much borrowing of material]

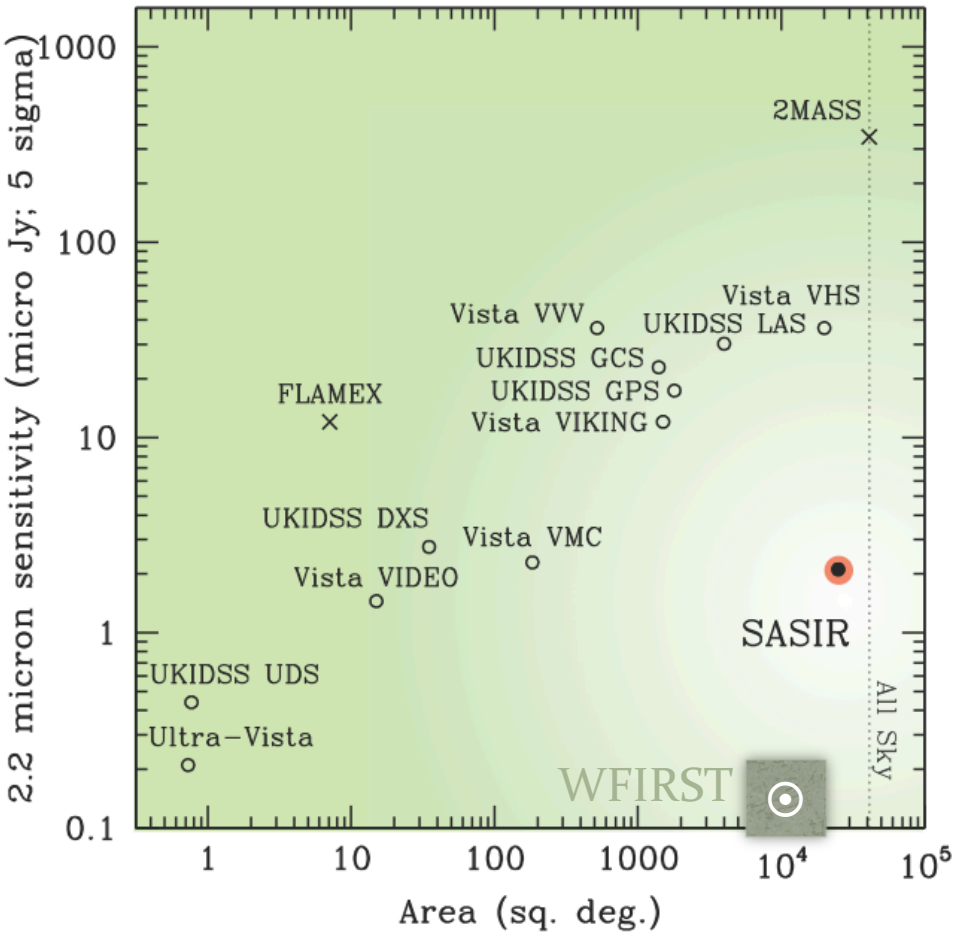
Historical Perspective

- Surveying the sky has been part of astronomical culture since antiquity.
- We are a discovery science.
- Technology advances lead to scientific advances.
  - depth
  - spatial resolution
  - areal coverage
  - data storage capabilities
  - data dissemination

WFIRST will take the next steps in all of these areas!

credit: Dan Stern + SASIR team





Motivation

- I was asked to review existing and future infrared survey capabilities *relevant for galactic science*.
- As background, last summer the WFIRST SDT convened an external advisory group for surveys. Advisors with galactic and z ~ 0 stellar populations interests included:
  - Sean Carey
  - Kem Cook
  - Lynne Hillenbrand
  - George Rieke
  - John Stauffer
  - Roeland van der Marel
- Any good ideas in these slides probably came from them; all the bad ideas are mine.

Motivation

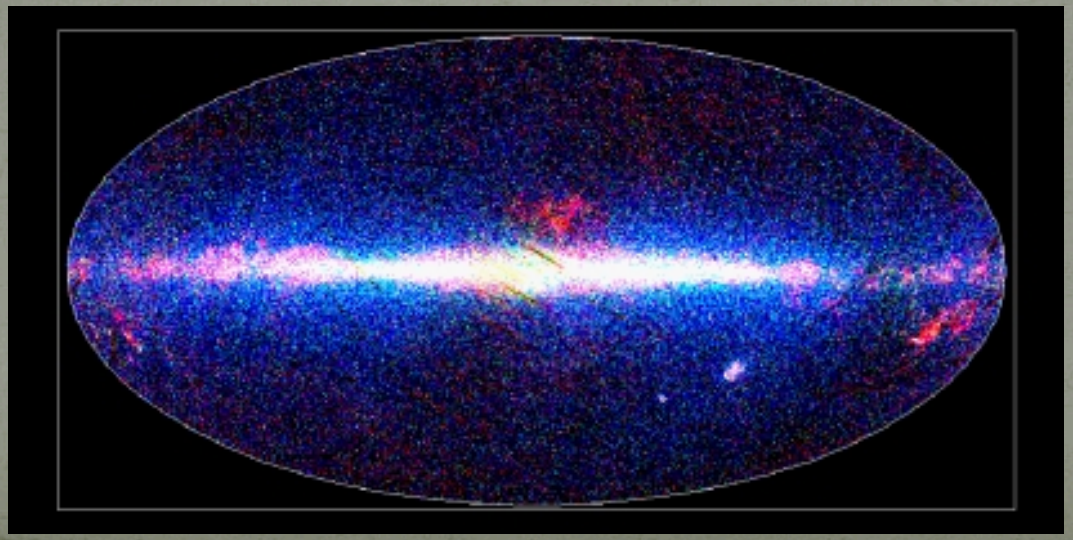
- Outline:
  - brief survey of surveys
  - what can WFIRST do? more/better? uniquely?

- There is the potential for significant scientific progress through collaboration and data sharing policies regarding existing/soon ground-based surveys.
- There is the potential for significant cost savings and enhanced capabilities on future space survey missions (specifically ESA/Euclid and NASA/WFIRST) through discussion, collaboration, optimization.
- Politics occasionally intervenes.....

Truly All-Sky Near-/Mid-Infrared Surveys

- 2MASS (1.2, 1.6, 2.2 um)
- WISE (3.4, 4.6, 12, 22 um)

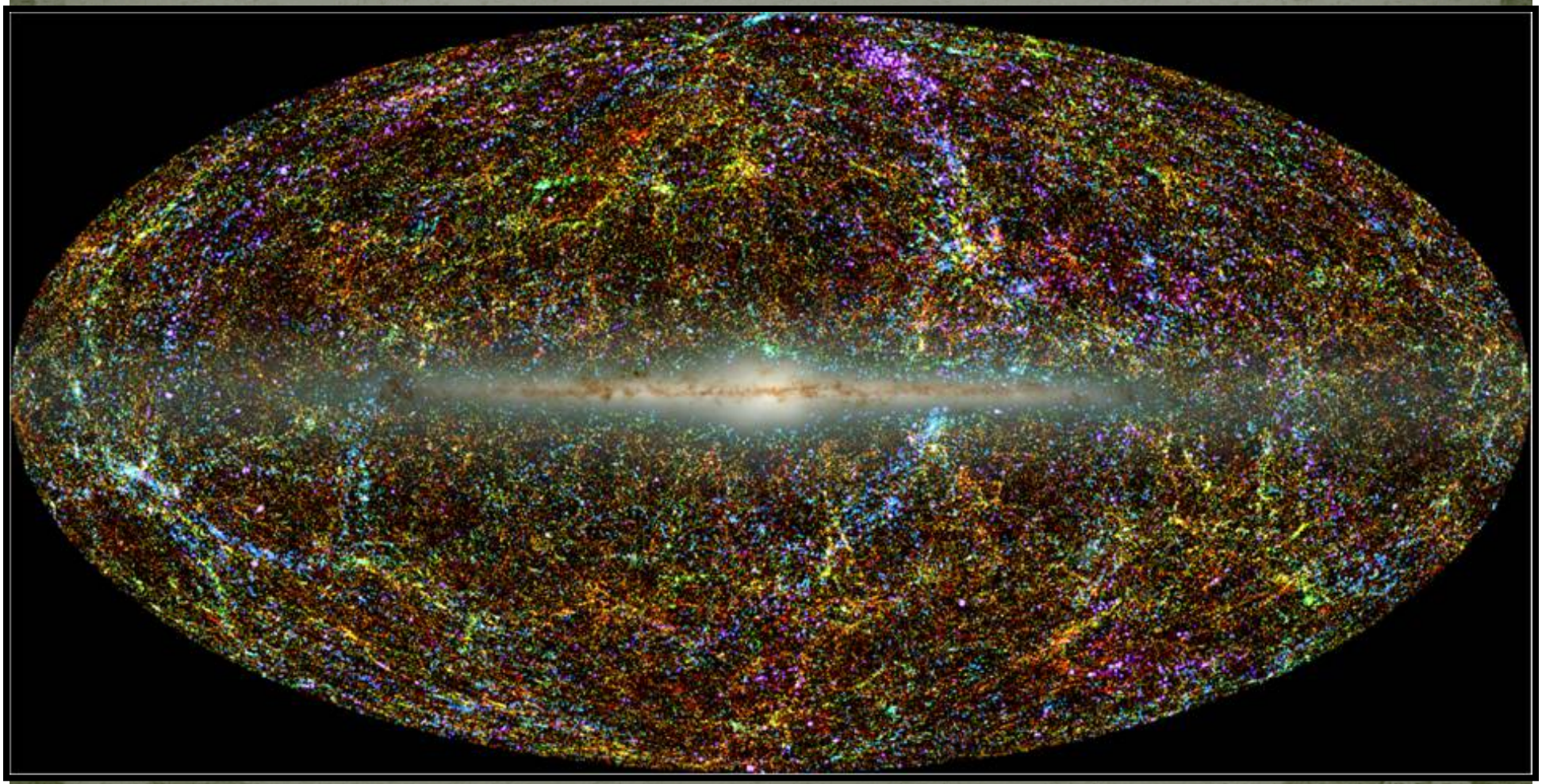
- IRAS (12, 25, + 60, 100 um) at 2-5' resolution
- AKARI (9, 18, + 65, 90, 140, 160 um) with 25-45" resolution



2MASS

- "2 Micron All Sky Survey"
- http://www.ipac.caltech.edu/2mass/
- First ground-based digital sky survey. 99.998% of the sky.
- 10-sigma point source sensitivity to J=15.8, H=15.1, K=14.3 at $|b| > 10^{o}$ [these and all other unspecified mags in this presentation are Vega system, of course]
- Seeing-limited resolution ~1.3-2"
- ~471 million point sources and 1.7 million extended sources
- Better than 3% photometry and 0.1" astrometry for point sources

2MASS stars and galaxies

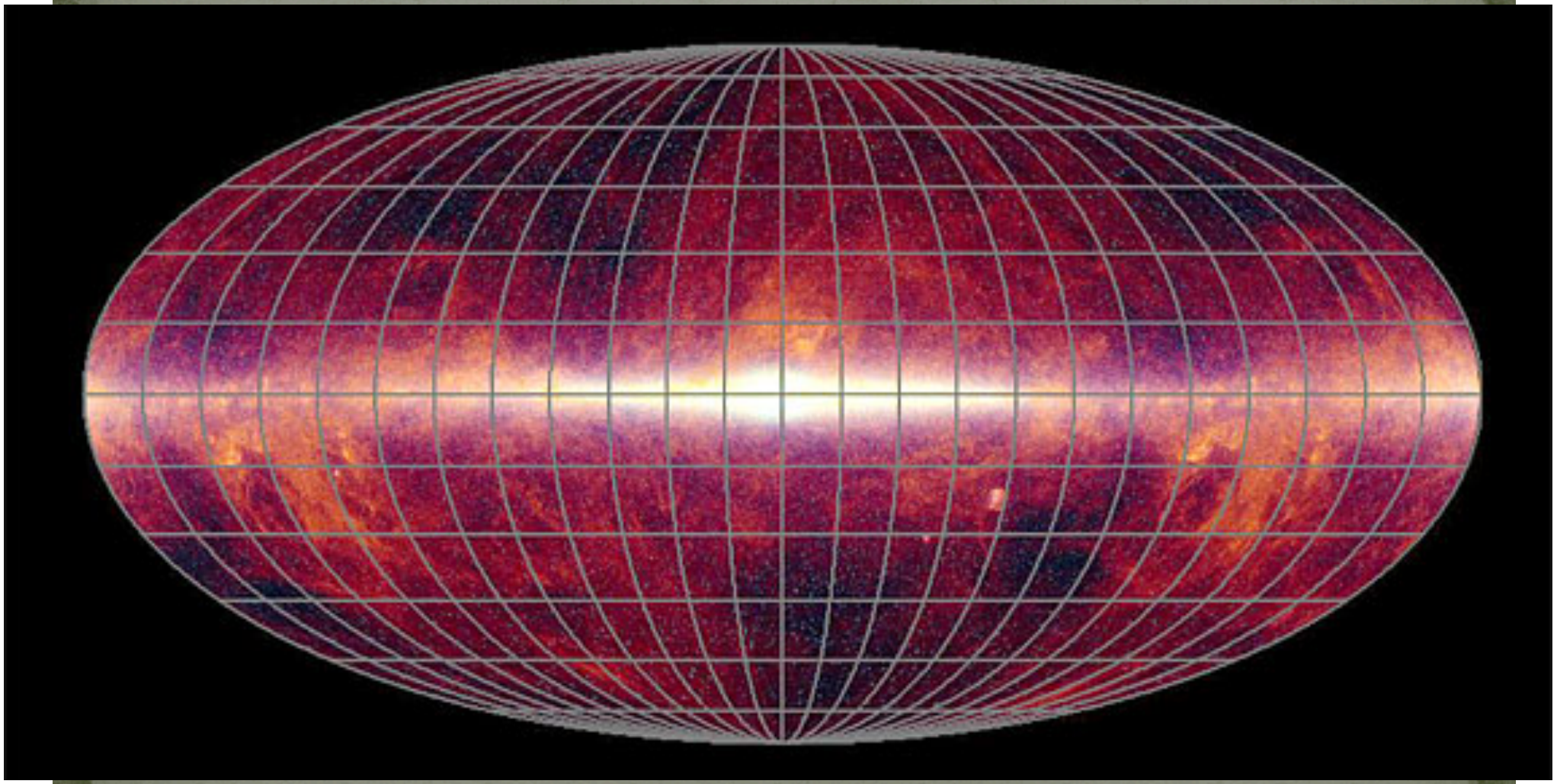


WISE

- "Wide-field Infrared Survey Explorer"
- http://www.ipac.caltech.edu/wise/
- Full-sky mapping to depth:
  W1 (3.4 um) = 0.08 mJy
  W2 (4.6 um) = 0.08 mJy
  W3 (12 um) = 0.8 mJy
  W4 (22 um) = 4 mJy

  (10^3 / 10^5 times deeper than IRAS / COBE at long / short bands, and comparable in νF_ν to UKIDDS YJHK and SDSS z)
- 6-12" resolution

WISE All-Sky Image



Non All-Sky but Significant s.r. Near-/Mid-Infrared Surveys

- DeNIS
- UKIDSS / GPS
- VISTA / VVV

near-infrared

- MSX
- Spitzer
- Herschel / Hi-GAL

mid and far-infrared

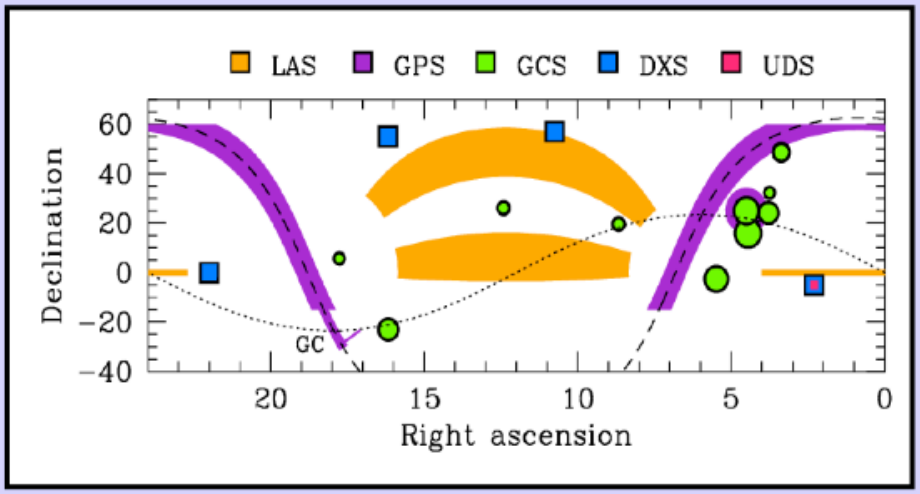
Next slides focus on galactic plane and star forming regions aspects of these surveys

UKIDSS - GPS

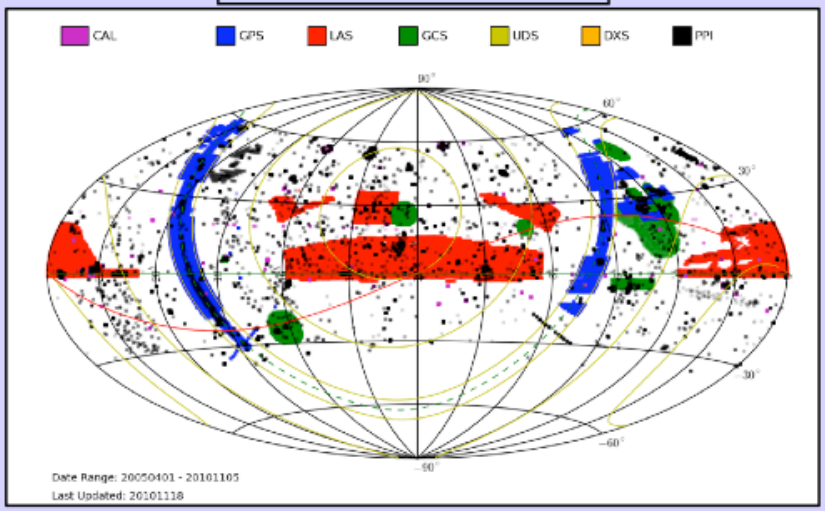
- "United Kingdom Infrared Deep Sky Survey"
- http://surveys.roe.ac.uk/wsa/
- UKIRT 3.8m telescope + WFCAM
  (4 x 2048^2 Hawaii-II arrays, 0.21 deg^2)
- 1844 deg^2 of the Northern sky, range of latitudes
- 5-sigma depth of K=18.1, H=19.0, J=19.8 plus some Y,Z
- 0.4" pixels (seeing limited resolution 0.8")
- ~2 billion sources
- 10 mas/year proper motions

http://wiki.astrogrid.org/pub/UKIDSS/Jan11Workshop/Lawrence-welcome.pdf

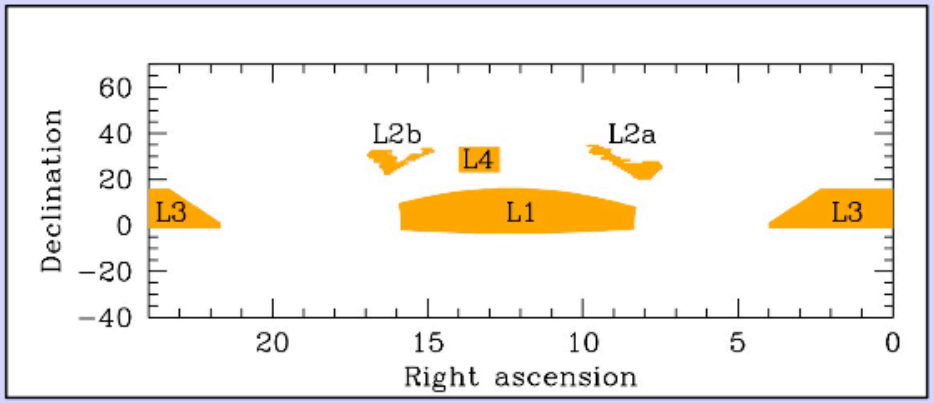
Original design



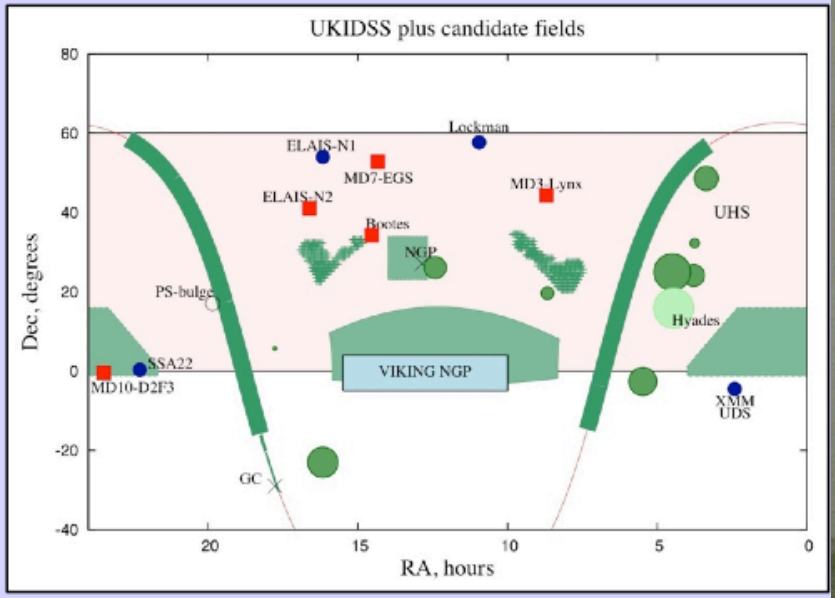
2010-Nov coverage



2009 LAS revision

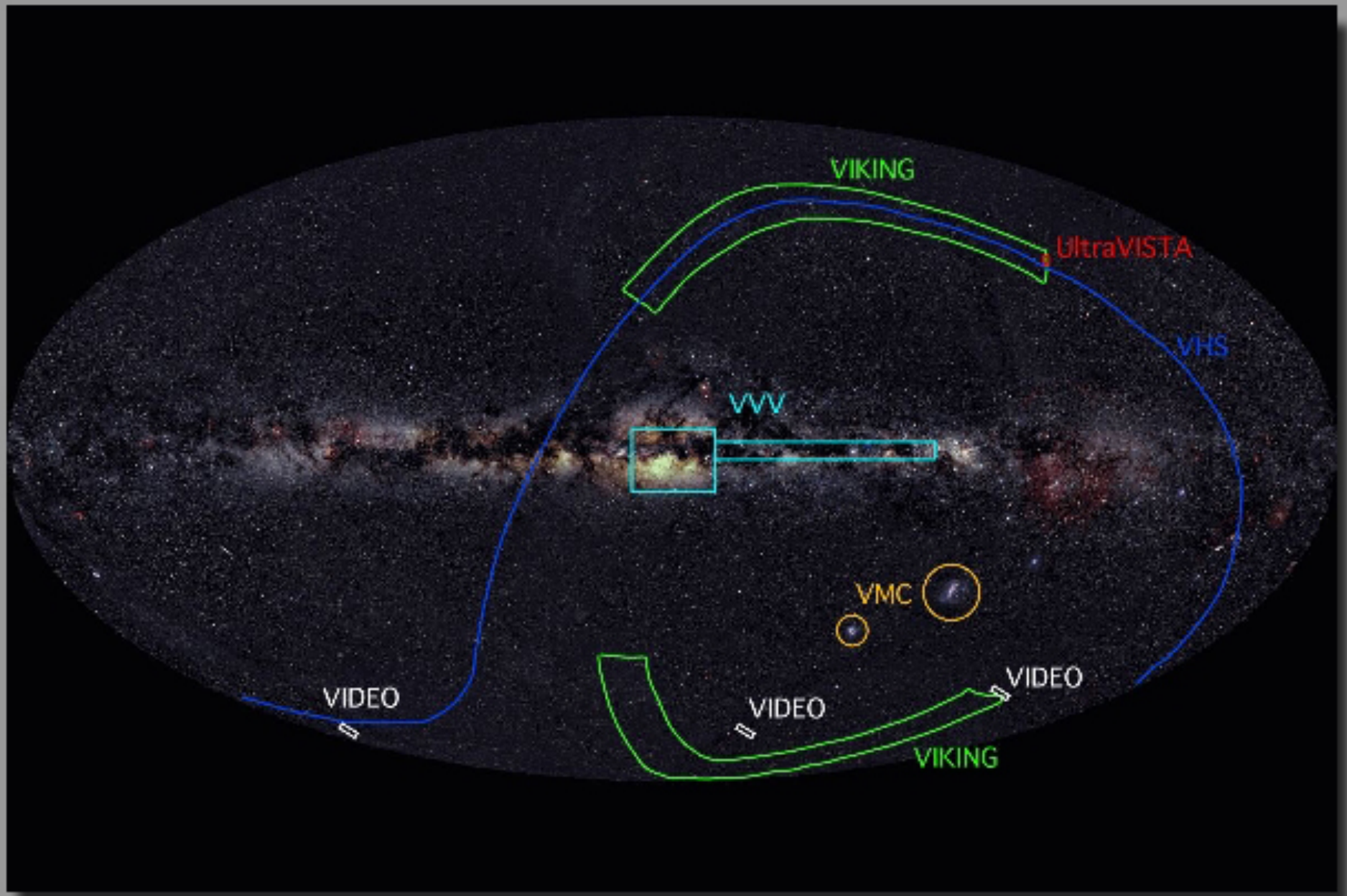


The future ?

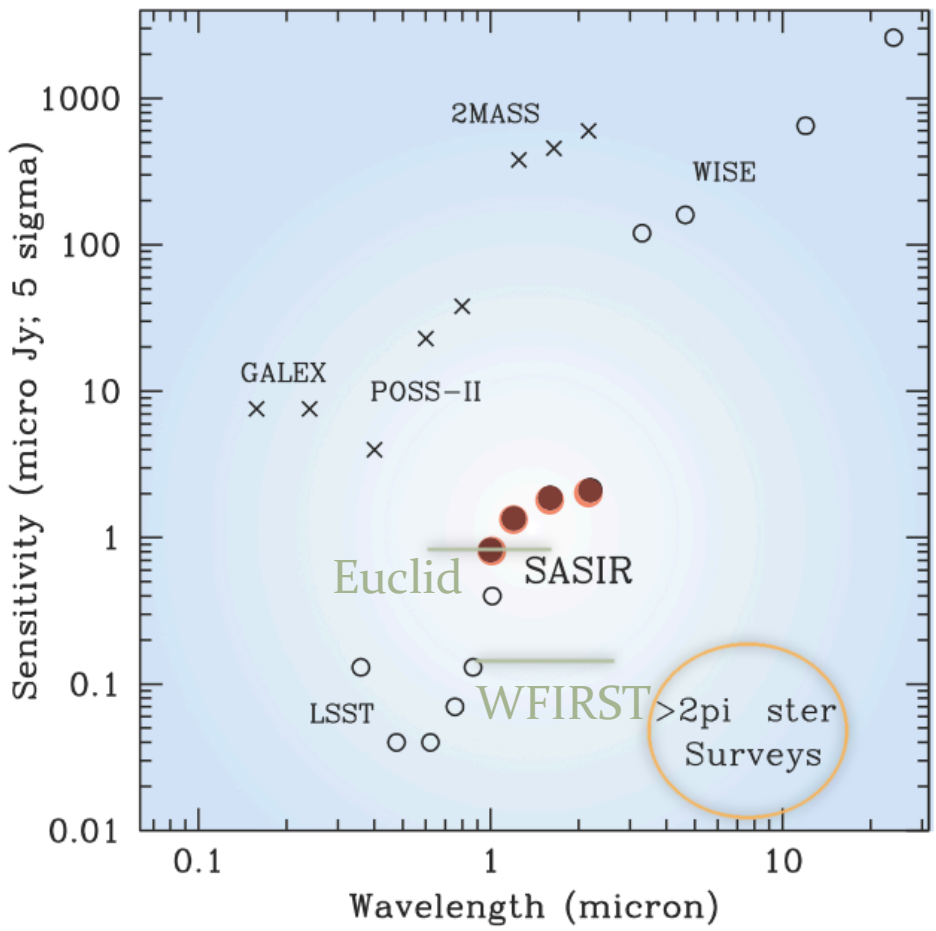


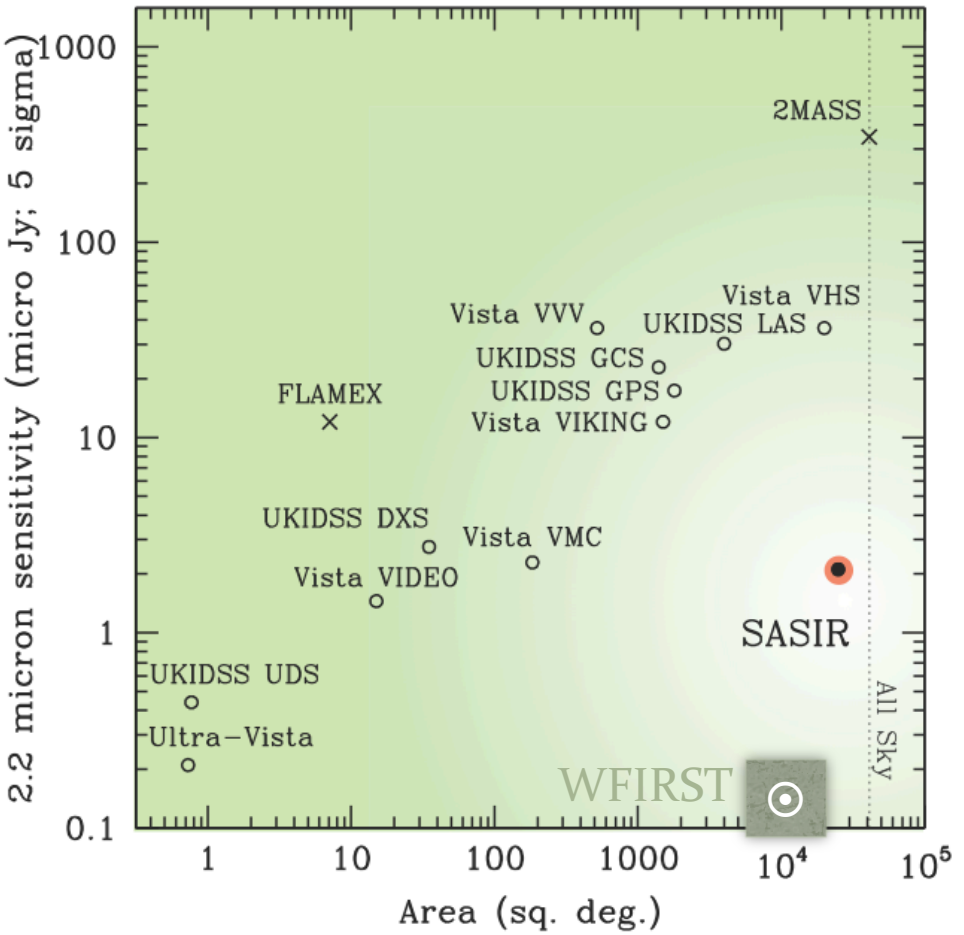
VISTA - VVV

- "VISTA Variables in the Via Lactea"
- http://horus.roe.ac.uk/vsa/
- VISTA 4 m telescope at Paranal + WFCAM (16 x 2048^2 arrays, 0.6 deg^2)
- 200 deg^2 of southern galactic plane + 300 deg^2 of bulge
- zYJHK to 10-sigma limits K = 18, z=22
- 0.2" pixels (seeing limited resolution 0.8" at K)
- ~80 epochs of time series data in Ks


VIKING
UltraVISTA
VHS
VVV
VMC
VIDEO
VIDEO
VIDEO
VIKING

credit: Dan Stern + SASIR team





SASIR concept

http://www.sasir.org

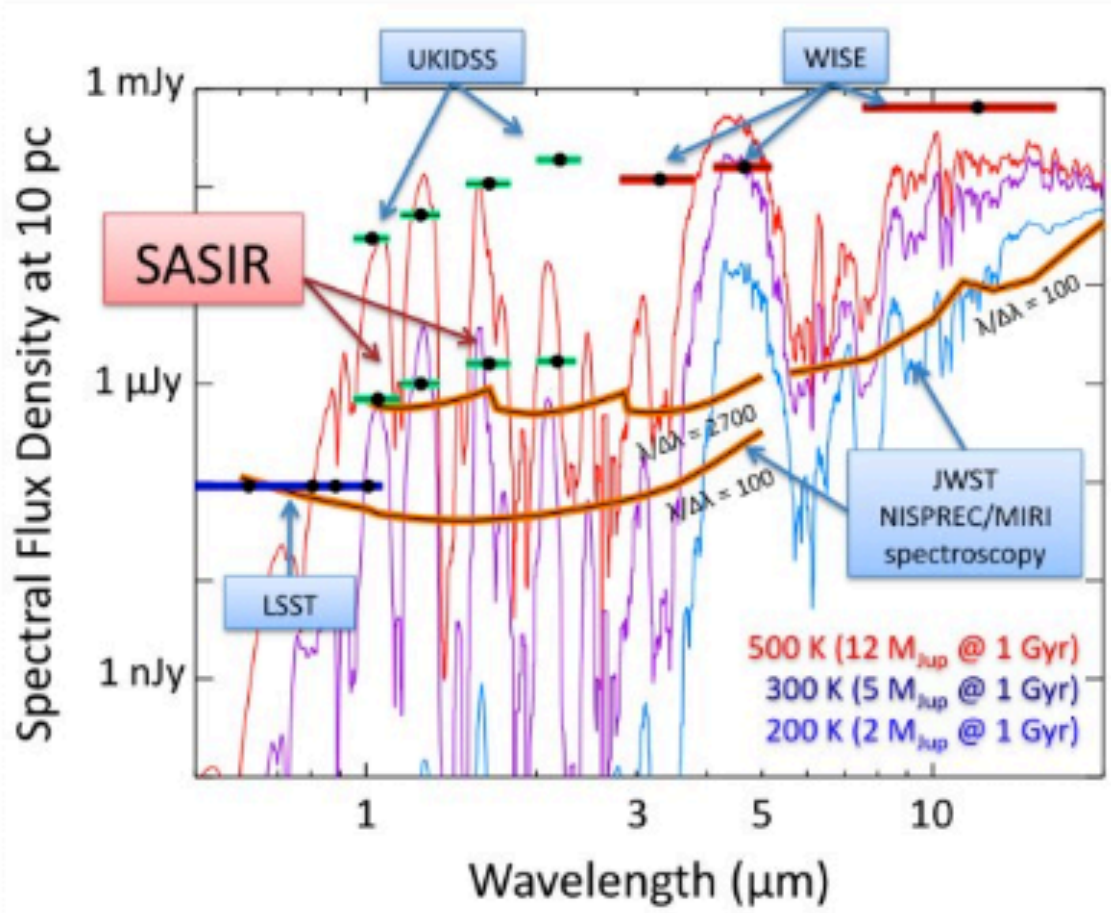


Figure 1 *Model spectra [5] for 500 K, 300 K and 200 K brown dwarfs (top to bottom), scaled to a distance of 10 pc. These models correspond to masses of 12, 5 and 2 Jupiter masses at an age of 1 Gyr, respectively. Sensitivity limits for current and proposed imaging surveys (including SASIR) and spectroscopic facilities (5σ in 1 hour) are indicated.*

Table 1. Nominal Sensitivities from SASIR Concept Design

Filter	Point Source Sensitivity Single Epoch (5-σ) [AB mag]	[μJy]	Point Source Sensitivity Survey (5-σ) [AB mag]	[μJy]	Extended Source Sensitivity Survey (5-σ per pixel) [AB arcsec^{-2}]	[μJy arcsec^{-2}]
Y	23.49	1.45	24.47	0.59	23.32	1.71
J	22.95	2.40	23.93	0.97	22.78	2.82
H	22.60	3.30	23.57	1.35	22.42	3.89
K_s	22.47	3.74	23.44	1.52	22.29	4.40

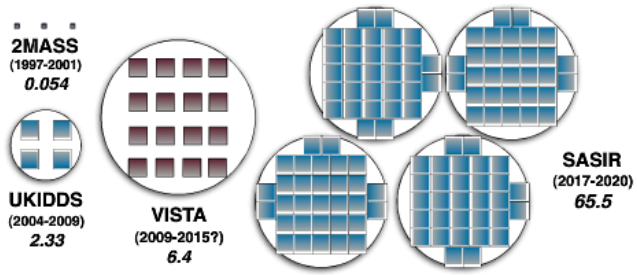


Figure 7 *To scale physical comparison of the focal planes of 2MASS, UKIDDS, VISTA and SASIR. The éntendue-couleur (m^2 deg^2 × number of simultaneous bands), the instantaneous light grasp, is shown for each facility.*

MSX

- “Mid-course Space eXperiment”
- http://irsa.ipac.caltech.edu/Missions/msx.html
- Survey wavelengths 8.3, 12.1, 14.7, 21.3 um
- Coverage $0^{o} < l < 360^{o}$ at $|b| < 5^{o}$ + IRAS gaps

Spitzer

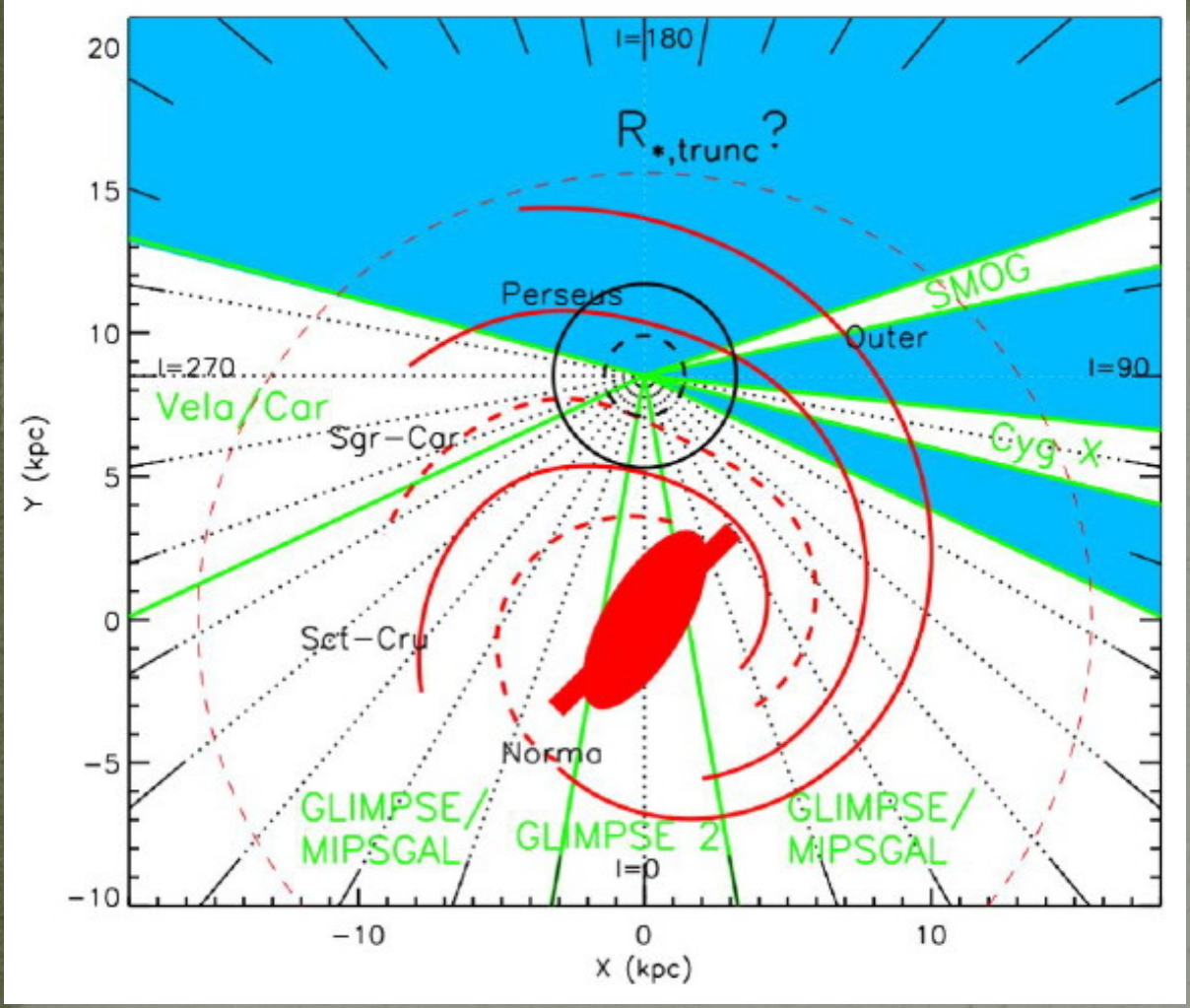
- FLS_GALACTIC
- GLIMPSE, GLIMPSE II, GLIMPSE 3D, GLIMPSE360, MIPSGAL
- CORES_TO_DISKS (c2d)
- GouldsBelt
- Taurus, Taurus-2
- Cygnus-X
- SMOG

3.6, 4.5, 5.8, 8 um
24, 70, 160 um

- ----------

- YSOVAR, YSOVAR2
- METCHEV-BROWN_DWARFS

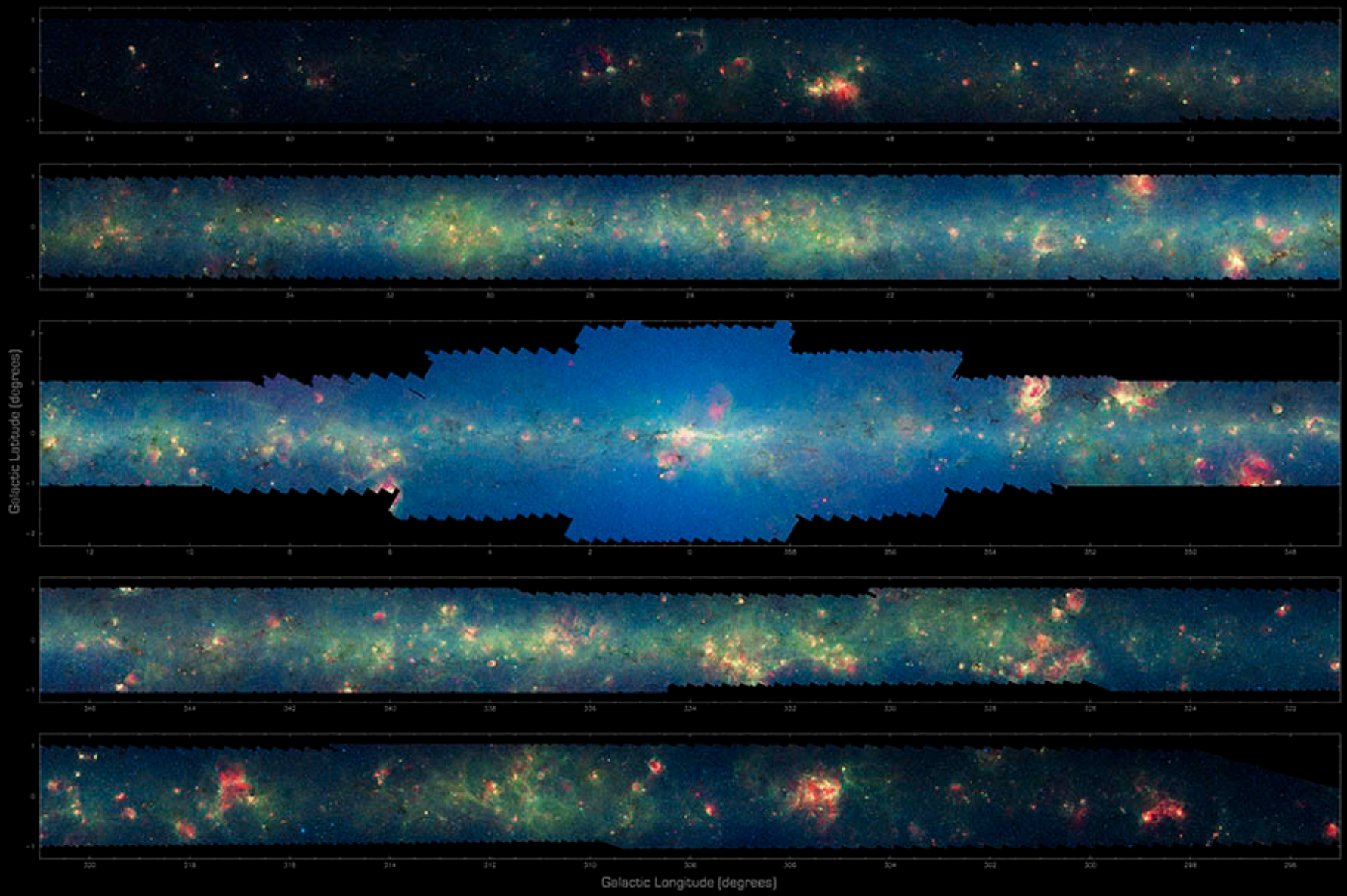
3.6, 4.5 um *time domain



http://www.astro.wisc.edu/sirtf/glimpse360/

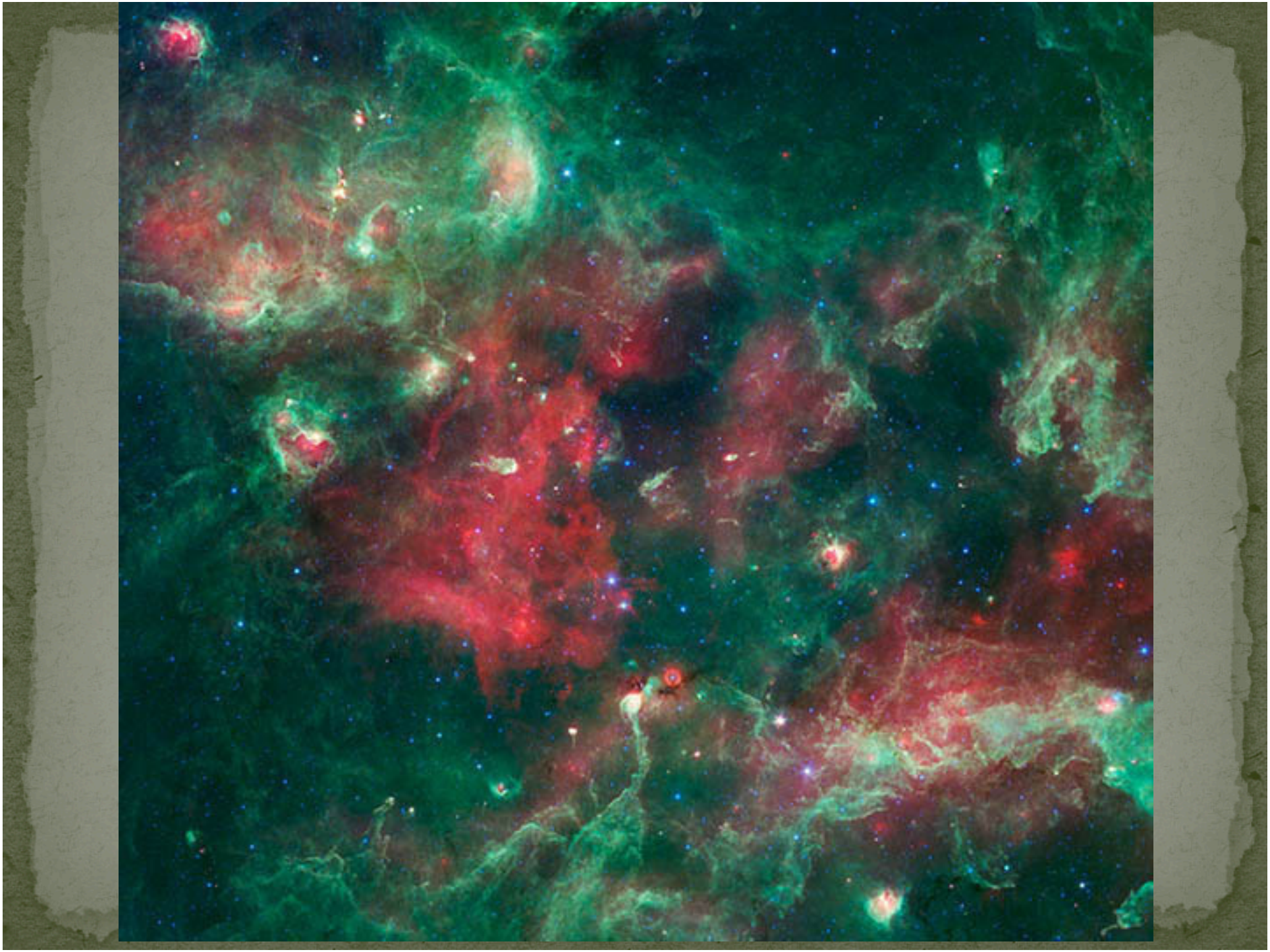
See talk by Sean Carey

The Galactic Plane showing the areas covered by previous surveys in white and the GLIMPSE360 survey in blue. The circles centered on the Sun shows the GLIMPSE360 detection limit distance for a solar type star (solid line) is about twice that of WISE (dashed line). The approximate positions of Galactic spiral arms (Taylor & Cordes 1993) are indicated in red. The dashed spiral arms have tangency points that show no excess star counts (Benjamin 2007) and may not be density wave arms. The central oval and bar represent the approximate extent of the central triaxial bulge/bar (Gerhard 2002; Cole & Weinberg 2002) and the Long bar (Hammersley et al. 2001; Benjamin et al. 2005). The radius marking the expected truncation or break in the exponential Galactic stellar disk is also shown with a dashed line.



The Infrared Milky Way: GLIMPSE/MIPSGAL Spitzer Space Telescope • IRAC • MIPS

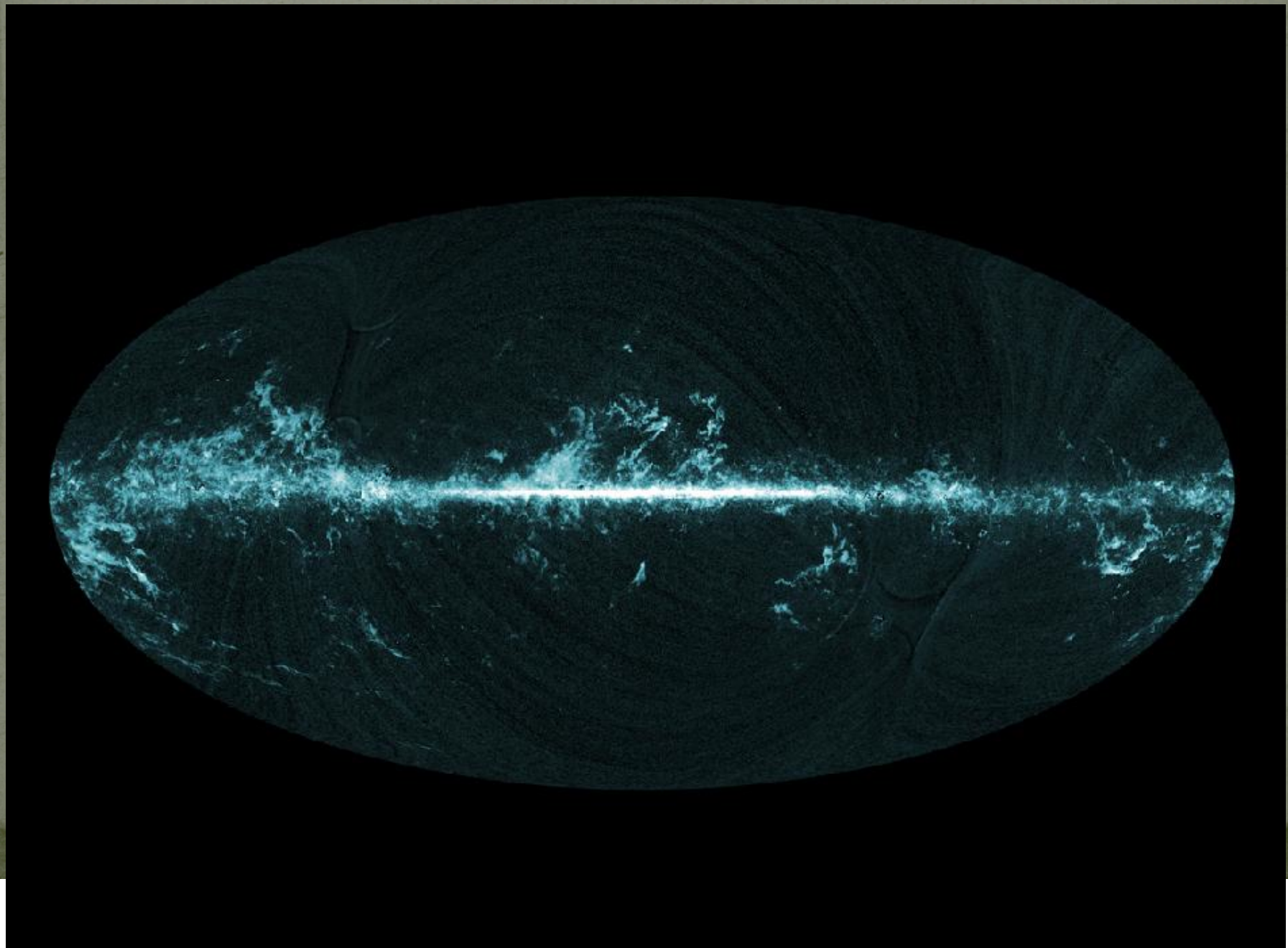
NASA / JPL-Caltech / E. Churchwell (Univ. of Wisconsin), GLIMPSE Team & S. Carey (SSC-Caltech), MIPSGAL Team ssc2008-11a



Herschel – HiGAL (+ GouldBelt)

- Far-infrared complement to e.g. Spitzer + UKIDSS/VISTA
- https://hi-gal.ifsi-roma.inaf.it/higal/
- Mapping to depth:
  70 um = 0.74 mJy
  120 um = 3.2 mJy
  175 um = 11 mJy
  250 um = 19 mJy
  350 um = 20 mJy
  500 um = 17 mJy
- Coverage $-60^{o} < l < 60^{o}$ at $|b| < 1^{o}$
- 4-40" spatial resolution (30 times better than IRAS)

Planck's "CO map" at 3mm



Near-and Mid Infrared Survey Science

- galactic structure on all scales (stars, extinction/ism)
- galactic stellar pops and star formation history
- ditto in magellenic clouds and local group galaxies
- identification of star clusters and sfr's in plane
- dusty young stars
- dusty evolved stars (cold and hot)
- faint red objects (brown dwarfs → planets)
- stellar/sub-stellar IMF
- proper motion *and parallax* studies of nearby objects
- time domain studies

Near-and Mid Infrared Survey Science Recent Highlights

- spiral arm and molecular cloud structure; extinction maps
- improved understanding of metallicity evolution and sfh
- many newly cataloged star clusters and sfr's
- primordial and debris disk statistics
- new info on and insight into dusty evolved stars
- increasingly cooler and lower mass objects found (L ➔T ➔Y)
- discrepancies between young cluster and field substellar IMF
- kinematic distances; identification of "moving groups" and high velocity stars; cluster membership
- robust variable star statistics; fortuitous observations of outbursting objects (young stars, cv's, supernovae); eclipsing binaries across the HR diagram; microlensing

What is best done at Near-IR vs longer or shorter wavelengths?

- Optimal in near-infrared
  - finding MLT dwarfs/subdwarfs
  - finding GKM giants and CSR stars
  - obscured and distant cepheids, RR Lyr, etc
  - providing ground truth for objects detected at longer/short λ
- Optimal longer than 2 um
  - finding dusty objects
  - finding objects in and behind dust obscured regions
  - finding Y dwarfs
- Optimal shorter than 1 um
  - BA subdwarfs
  - white dwarfs
  - extinction mapping

Multi-Wavelength Complementarity ➔ Spectral Energy Distributions

- Gamma ray – INTEGRAL, Fermi
- X ray – *ROSAT*, 2XMM, Chandra surveys, eROSITA
- Ultraviolet - GALEX
- Optical – SDSS, *UVEX/IPHAS*, *RAVE*, ASAS, CRTS, PTF, *VPHAS+*, PanSTARRS, SkyMapper, Subaru/ HyperSuprimeCam, GAIA, LAMOST, BigBOSS??, ngCFHT??, LSST??
- Near/Mid-Infared – (covered in previous slides)
- Far-Infrared – BLAST, Herschel/HiGal, Planck
- Sub-mm/mm – CSO (Bolocam GPS), JCMT (SCUBA-2 JPS and SASSy), APEX (ATLASGAL)
- Radio – NVSS, FIRST, LOFAR?? MWA?? (G)ASKAP??

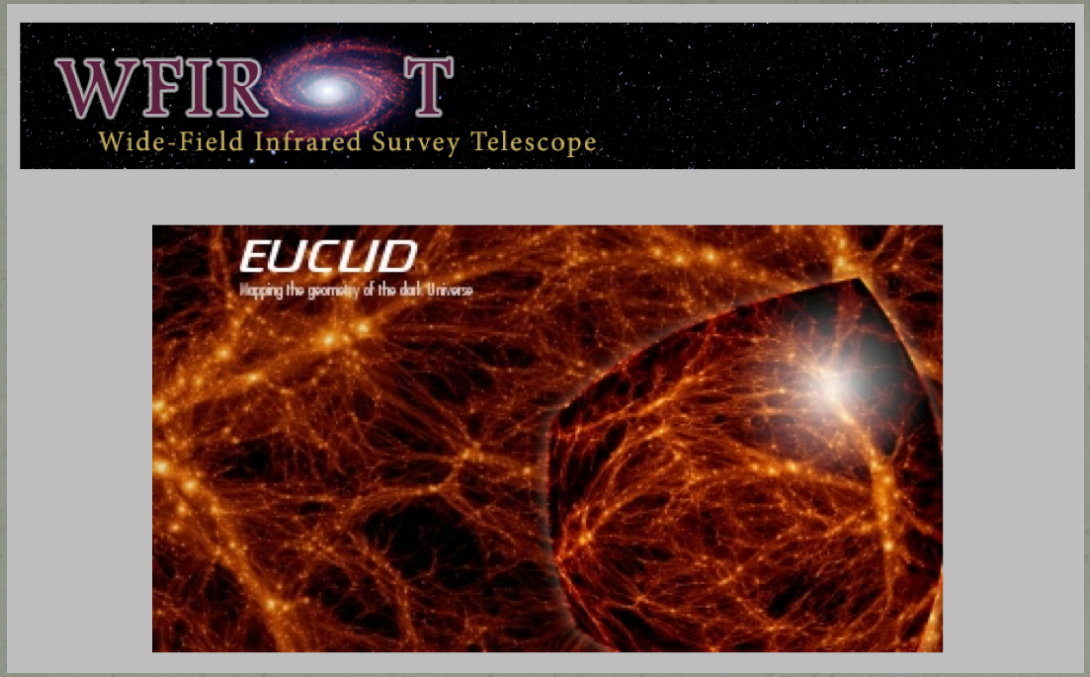
[non-galactic plane surveys are not listed, eg DES]

Historical Perspective

- Surveying the sky has been part of astronomical culture since antiquity.
- We are a discovery science.
- Technology advances lead to scientific advances.
  - depth
  - spatial resolution
  - areal coverage
  - data storage capabilities
  - data dissemination

WFIRST will take the next steps in all of these areas!

The Next Great Leap Forward in NIR



- Euclid: ~15,000 total high latitude deg^2 to m_{AB} ~24
- WFIRST: ~2700/year high latitude deg^2 to m_{AB} ~26
  + ~1500 low latitude (plane) deg^2 to confusion limit

- For galactic science:
  - *where* you point is important!
  - filter choice dictates achievable science

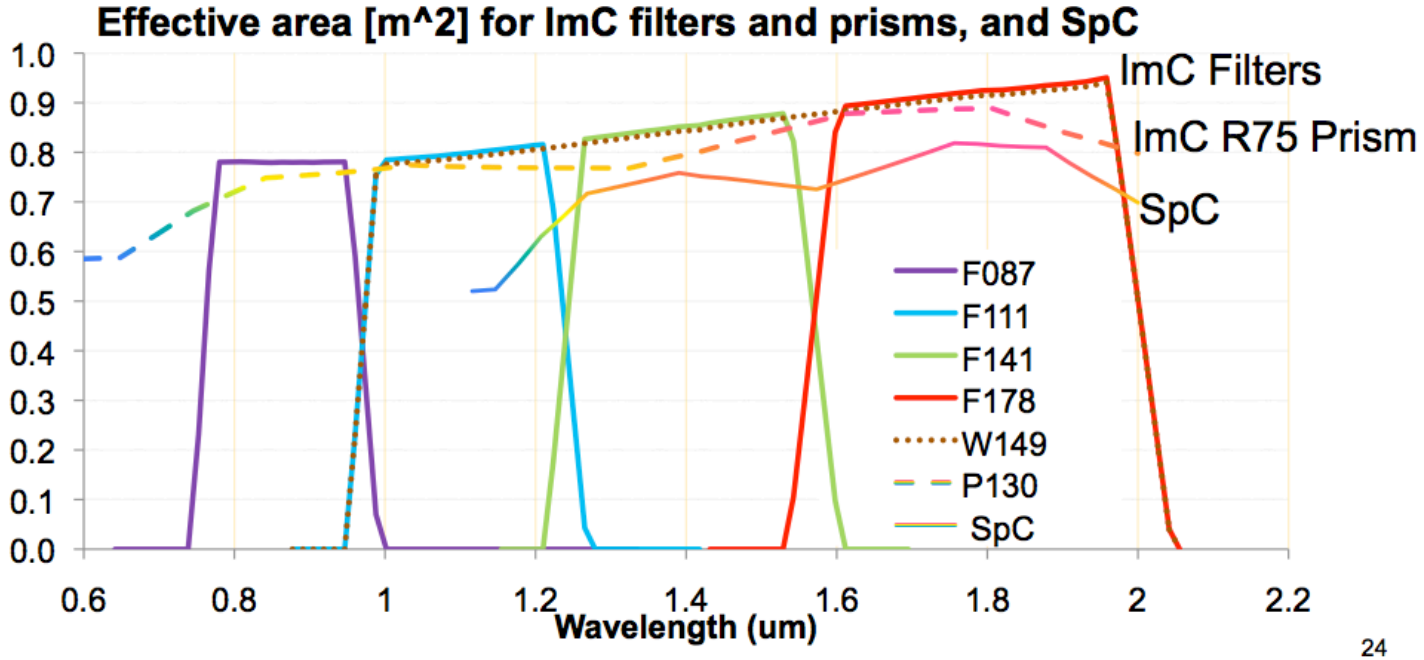
Filter Discussions

slide material from Green/Schecter/SDT in 2011; possibly obsolete now !!!!

Throughput

- Plot shows effective areas for each instrument configuration: Each of 2 identical Spectrometer channels (SpCs), and each element in the Imager filter wheel, per filter table below.

name	min	max	center	type
F087	0.760	0.970	0.865	ImC filter
F111	0.970	1.240	1.105	ImC filter
F141	1.240	1.570	1.405	ImC filter
F178	1.570	2.000	1.785	ImC filter
W149	0.970	2.000	1.485	ImC filter
P130	0.6	2	1.3	R75 ImC prism
SpC	1.114	2	1.557	R200 SpC prism



Capabilities of Interest for Galactic Science

- broad coverage [0.8] – [2.4] um colors, or color limits
  - hearty congratulations on recent adoption of a ~K-band!
  - even if not optimally sensitive b/c of telescope heating, we'll take it.
- a filter in the 3-5 um region for Y dwarfs
  - could think about moving even redder than K if no impact to RoM
- grism spectroscopy
  - interesting everywhere confusion allows, for low mass objects
- proper motions of known and newly discovered objects
  - GAIA + LSST will cover r = 6 to 24+, but infrared needed
- time domain possibilities
  - repeated deep/accurate coverage of selected regions
  - some (not all) science would require rapid response follow-up

What will be left for WFIRST to do in the Galaxy?

- wavelength complement to Spitzer/GLIMPSE + WISE to red, and LSST to blue
  all kinds of science possibilities when measuring (cool) stars at peak of SED
- complement WISE in pushing field brown dwarf detection to the end of the IMF
- open cluster membership and IMF to 5-10 M_{jup} from deep+wide approach (+ p.m.)
- globular clusters and helium white dwarfs

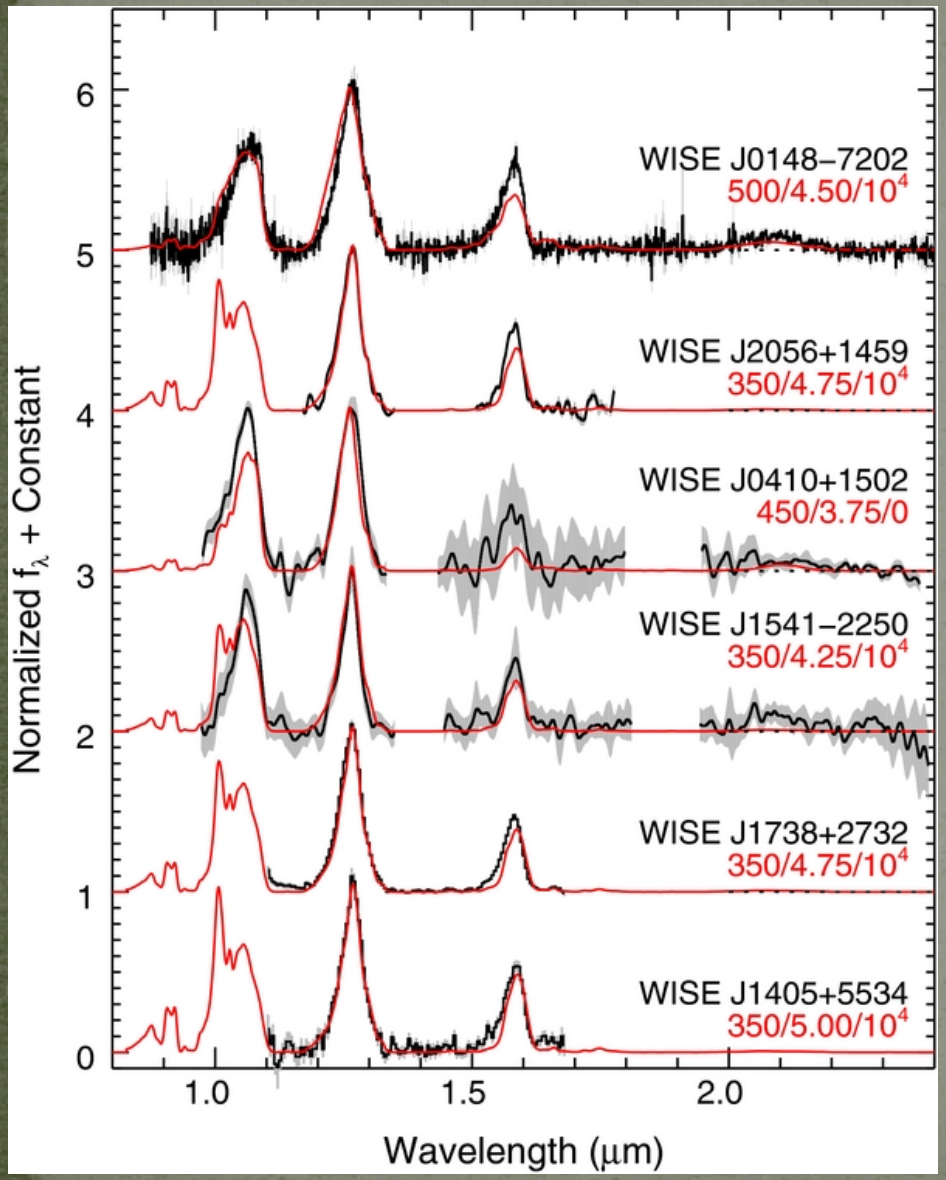
  See talk by Jason Kalirai
- stellar streams, especially close to and through the galactic plane

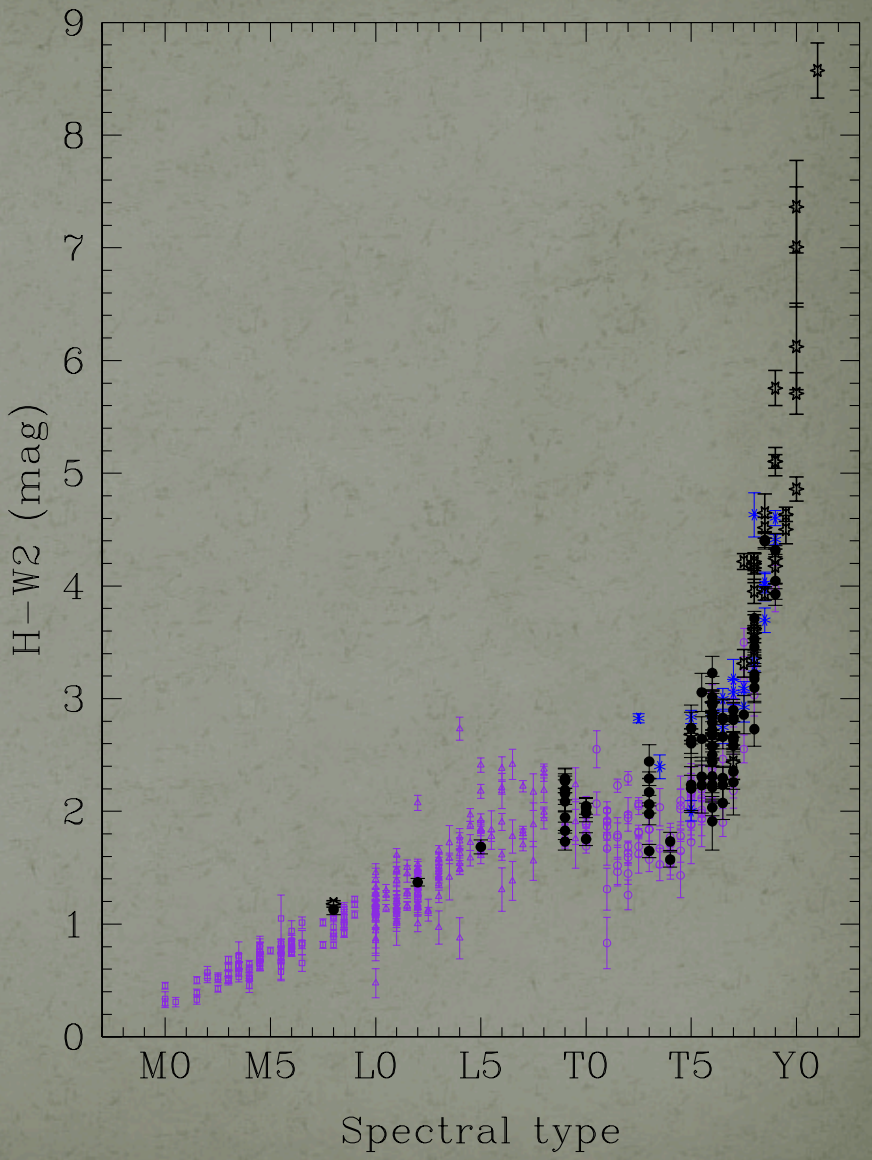
  See talk by Carl Grillmair
- high resolution extinction maps, even better when combined with GAIA + LSST
- advances in galactic structure, especially far side

  See talk by Sean Carey

  inner galactic plane likely confusion-limited so plan for |l| > 30 GPS
-

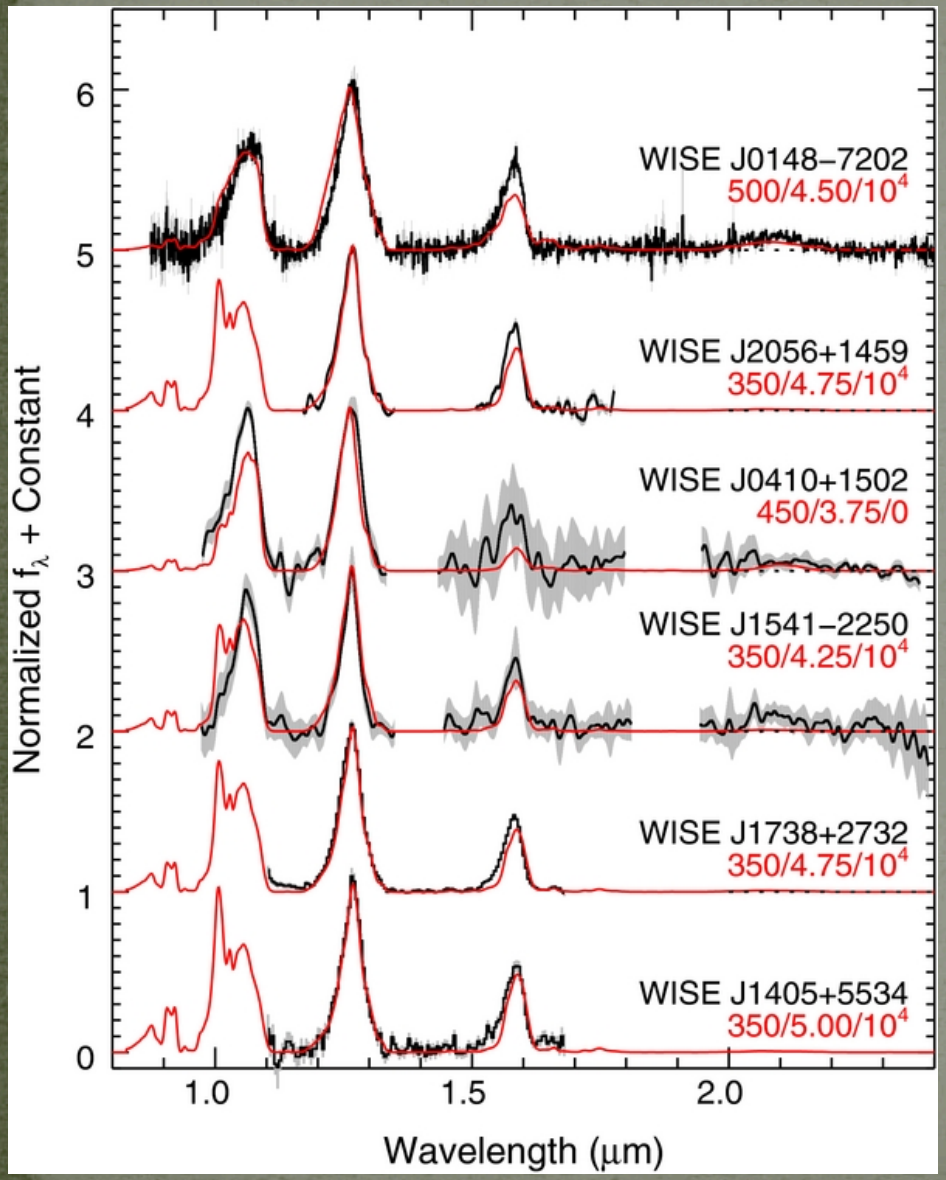
Y dwarfs are Red and Faint

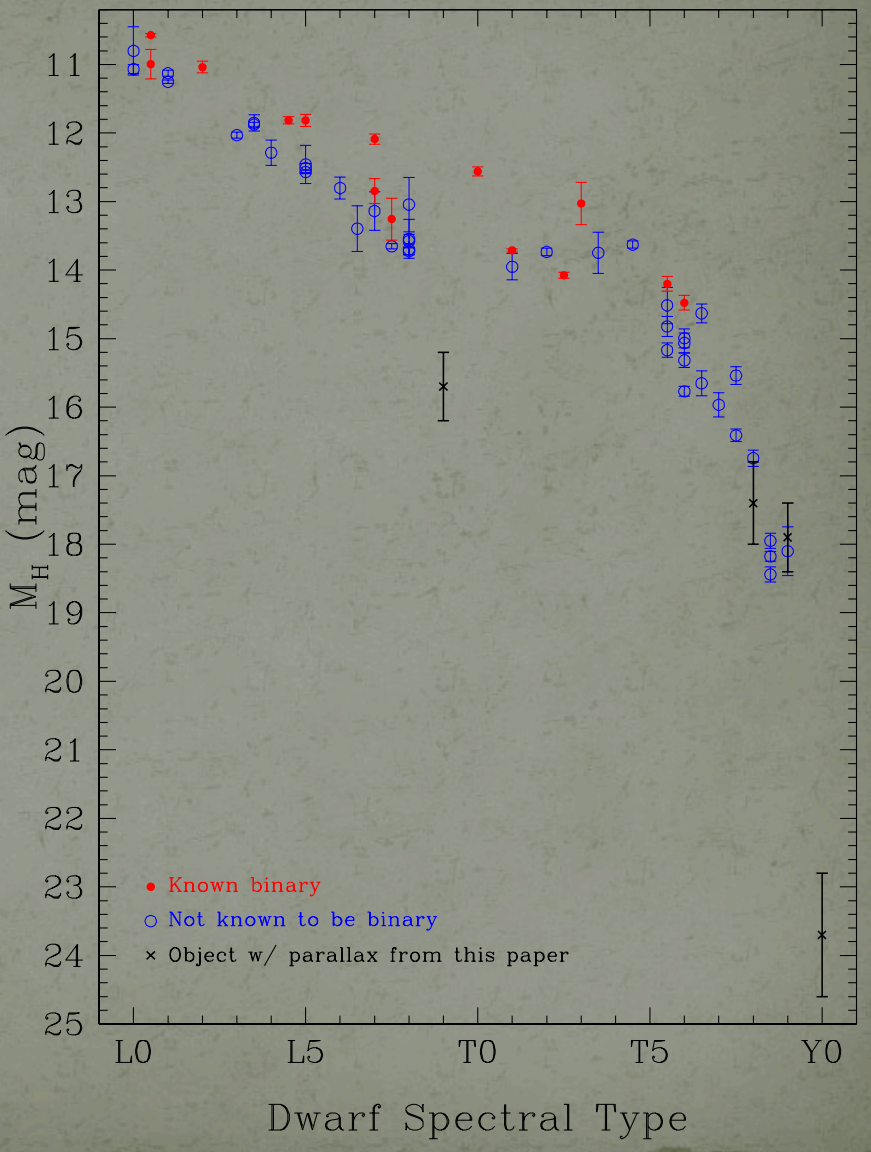




Cushing et al. 2012; Kirkpatrick et al. 2011

Y dwarfs are Red and Faint





Cushing et al. 2012; Kirkpatrick et al. 2011

This Model is for an Object at just 5 pc !

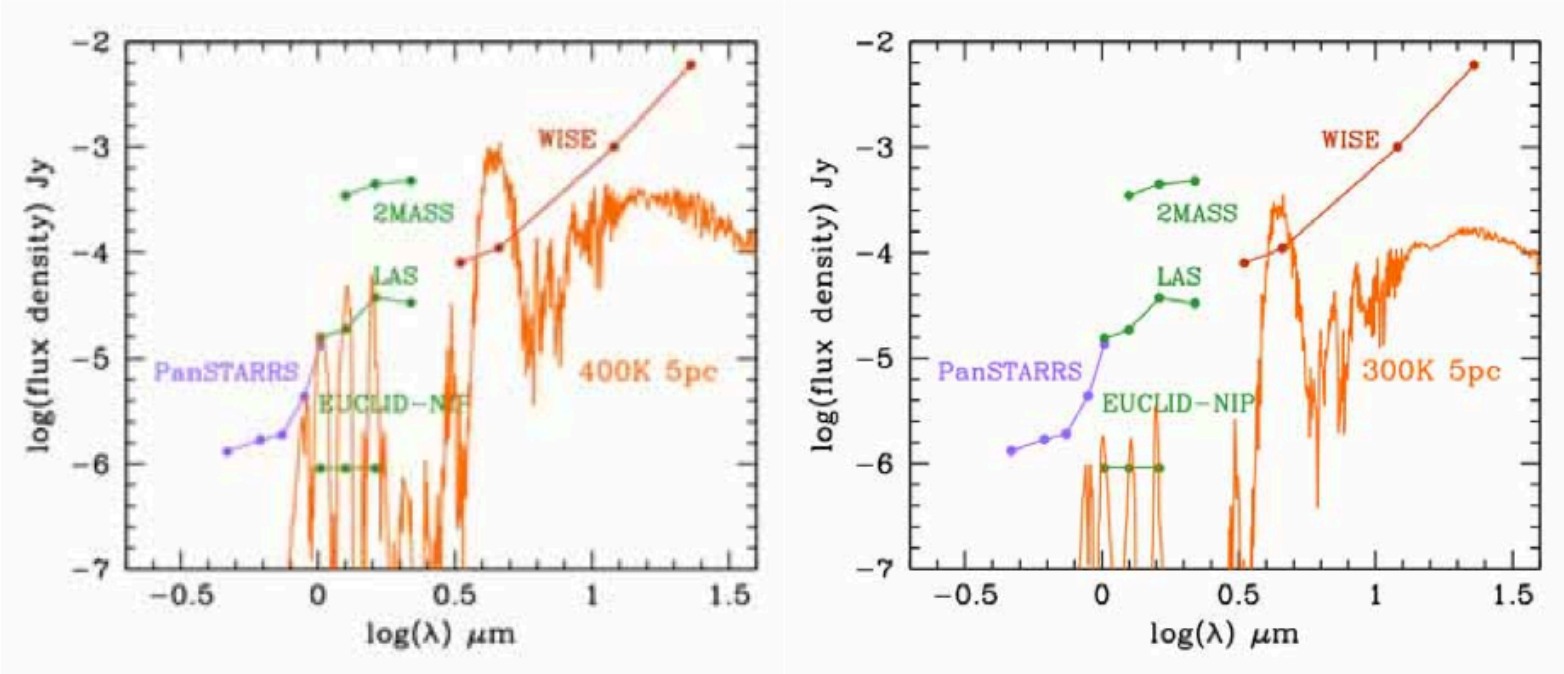


Figure 2.8: 5σ point-source depths of a number of surveys as a function of wavelength: PanSTARRS, 2MASS, UKIDSS-LAS, Euclid-NIP, and WISE. Overplotted are Burrows' model spectra for Y dwarfs of the quoted effective T_{eff} and distance. Only Euclid has the depth to confirm WISE detections of the coolest brown dwarfs with T_{eff}~300K.

Euclid definition study report
http://arxiv.org/pdf/1110.3193.pdf

Where is the End of the IMF in Clusters?

5 Myr old cluster, low extinction

120 Myr old cluster, little extinction

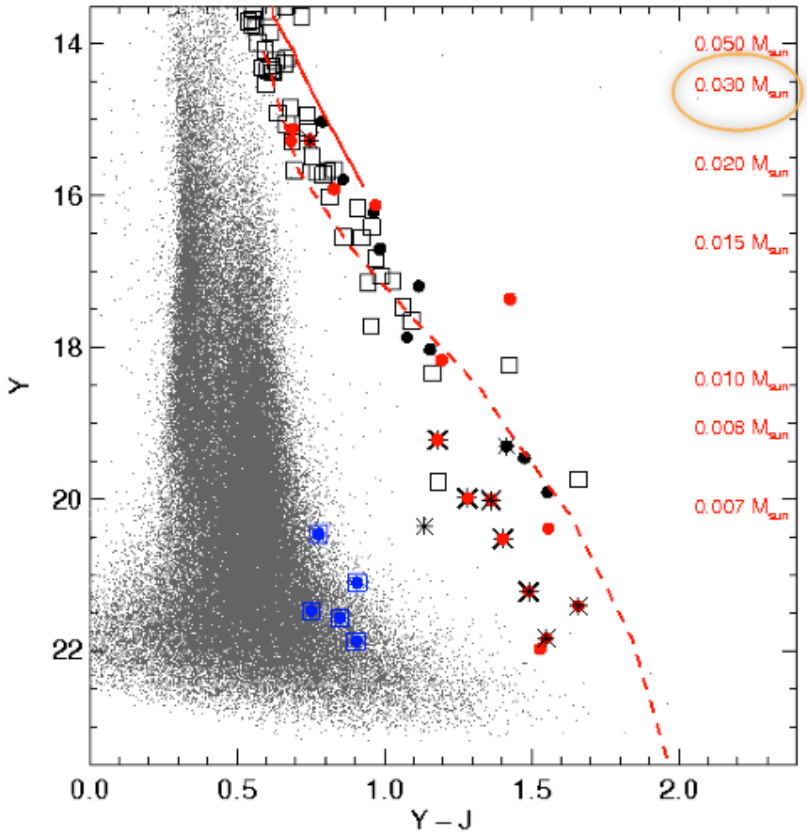
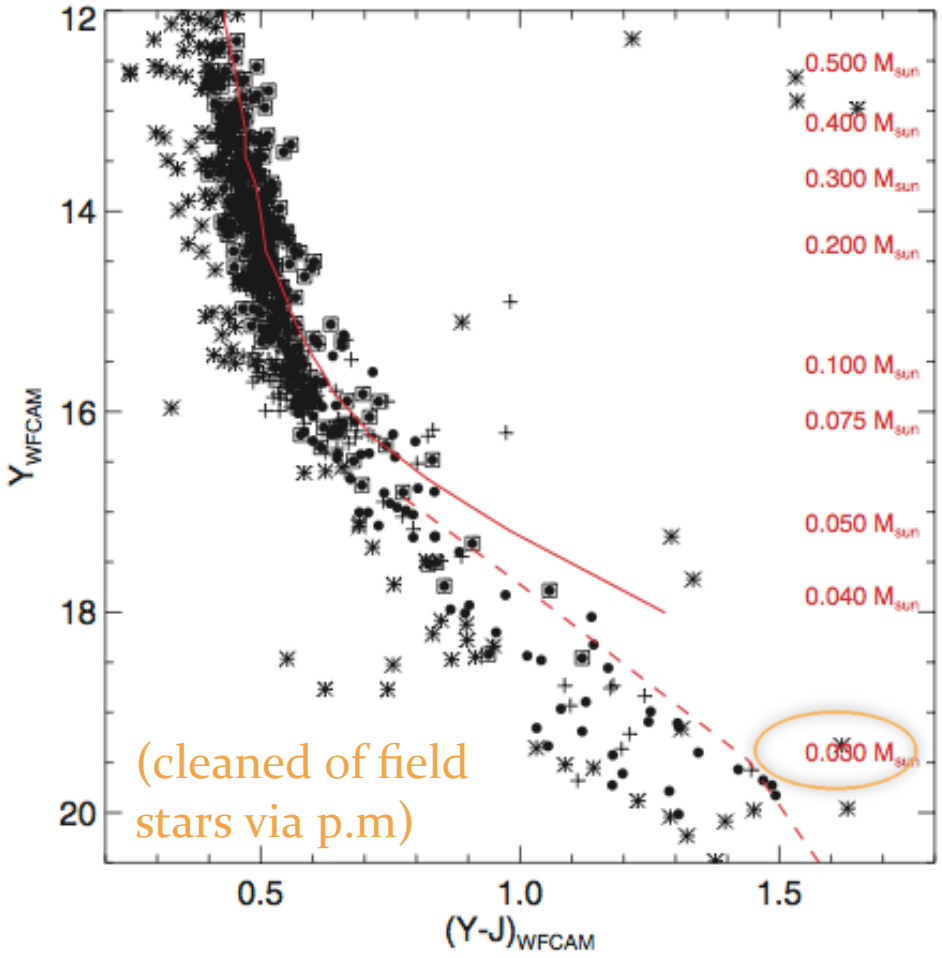


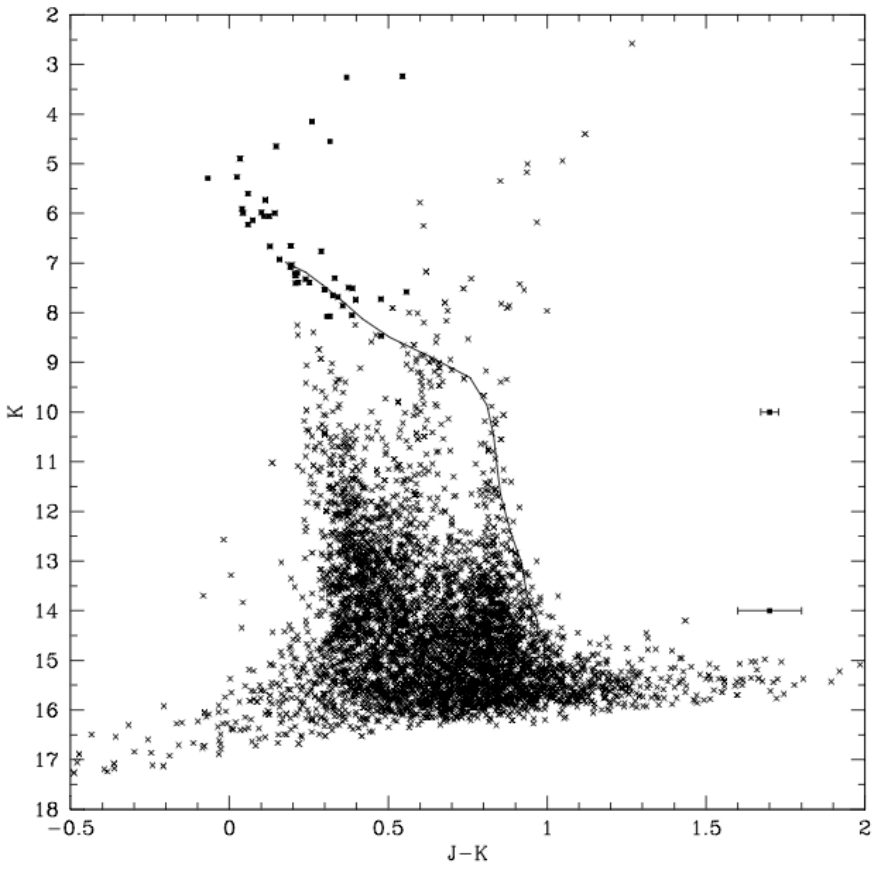
Figure 1. $(Y-J,Y)$ colour-magnitude diagram for ∼1.7 squa degree in USco. The small dots are all sources detected alo the line of sight of the association. Open squares are spectro- scopically confirmed members of the USco association from the UKIDSS GCS (Lodieu et al. 2007, 2008). Black filled circles are photometric candidates identified in the deep YJ survey alone, the red circles being new ones. Asterisks are later classified as photometric and/or spectroscopic non members using additional datasets presented in this paper. Blue circles with blue open



[Lodieu et al. 2011; 2007]

To Disentangle Age and Extinction from Mass, Need Multi-Color Data + P.M.

500 Myr old cluster, no extinction



[Casewell et al. 2006]

1 Myr old cluster, high/variable extinction

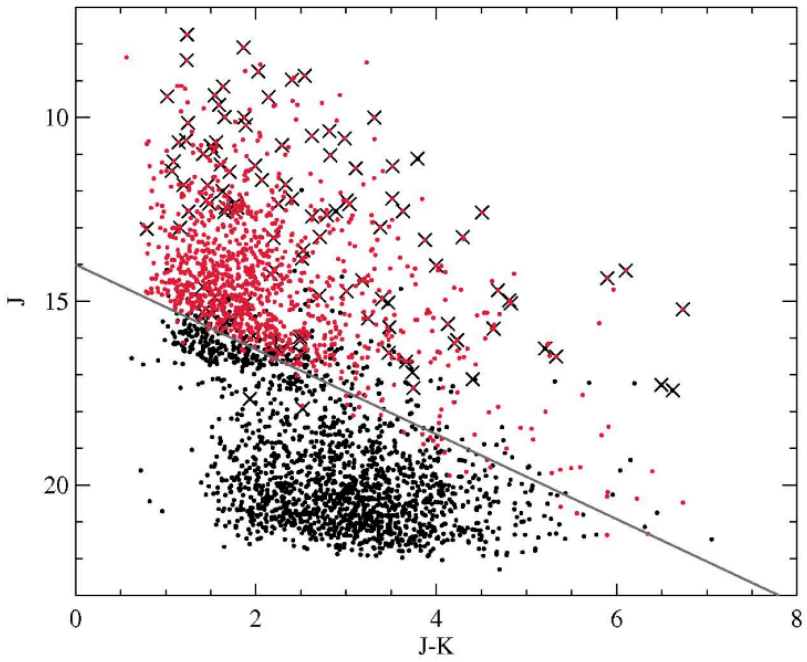


FIG. 7.— Near-infrared color-magnitude diagram for the sources in ρ Oph, based on MOIRCS and 2MASS photometry. Spectroscopically confirmed stellar and substellar members (Wilking et al. 2008, Erickson et al. 2011, Alves de Oliveira et al. 2010, and this work) are marked with crosses; objects with Spitzer counterpart are shown in red. The solid line shows the approximate limit of the combined $JK - Spitzer$ catalog.

[Muzic et al. 2011]

Non-uL Exoplanet Science

- Transiting planet searches in microlensing monitored fields.
- Astrometric planet searches in microlensing fields.
- Mapping the 115 deg^2 Kepler field.
- Grism spectroscopy of known nearby transiting systems (??)

(ideas contributed by SDT member Angelle Tanner)

Additional Considerations: Spectroscopy

- spectroscopy removes many degeneracies for stars
  - metallicity
  - surface gravity
  - effective temperature
  - distance
  - extinction
- spectroscopy moves us from pictures to physics
- but, as has always been true, existing and planned spectroscopic resources lag existing photometric capabilities.

Additional Considerations: "Astro-informatics"

- surveys can lead to data overwhelm!
- much recent computer science attention to:
  - band merging of photometry
  - identification of rapidly moving objects
  - comparison to historical or "static sky" images (for both photometric and astrometric purposes)
  - automated source classifiers
  - realization of higher level science goals
- need attention to data handling and dissemination

Summary

- Proliferation of large scale mid-infrared, near-infrared and optical surveys over last decade, beginning with 2MASS.
- Nevertheless spatial gaps in modern near-infrared surveying to limit ~18-20'th mag remain. 24'th sounds fabulous to any galactic astronomer.
- The coverage and depth of WFIRST will be unprecedented.
- Improved precision in near-infrared photometry and astrometry leads to new science. This is going to be great!
- The "three bullets" case for space-driven galactic science is still open to discussion. Thinking less evolved than for DE / uL.
- There are innumerable areas of potential interest for GOs.
- Filter choices should be made with all communities in mind.