Queen's University Belfast

High Contrast Imaging with Spitzer

Constraining the Frequency of Giant Planets out to 1000 AU Separations

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Thanks to: Markus Janson (Stockholm University) & Joe Carson (College of Charleston)

High Contrast Imaging with Spitzer : Constraining the Frequency of Giant Planets out to 1000 AU separations.

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ABSTRACT

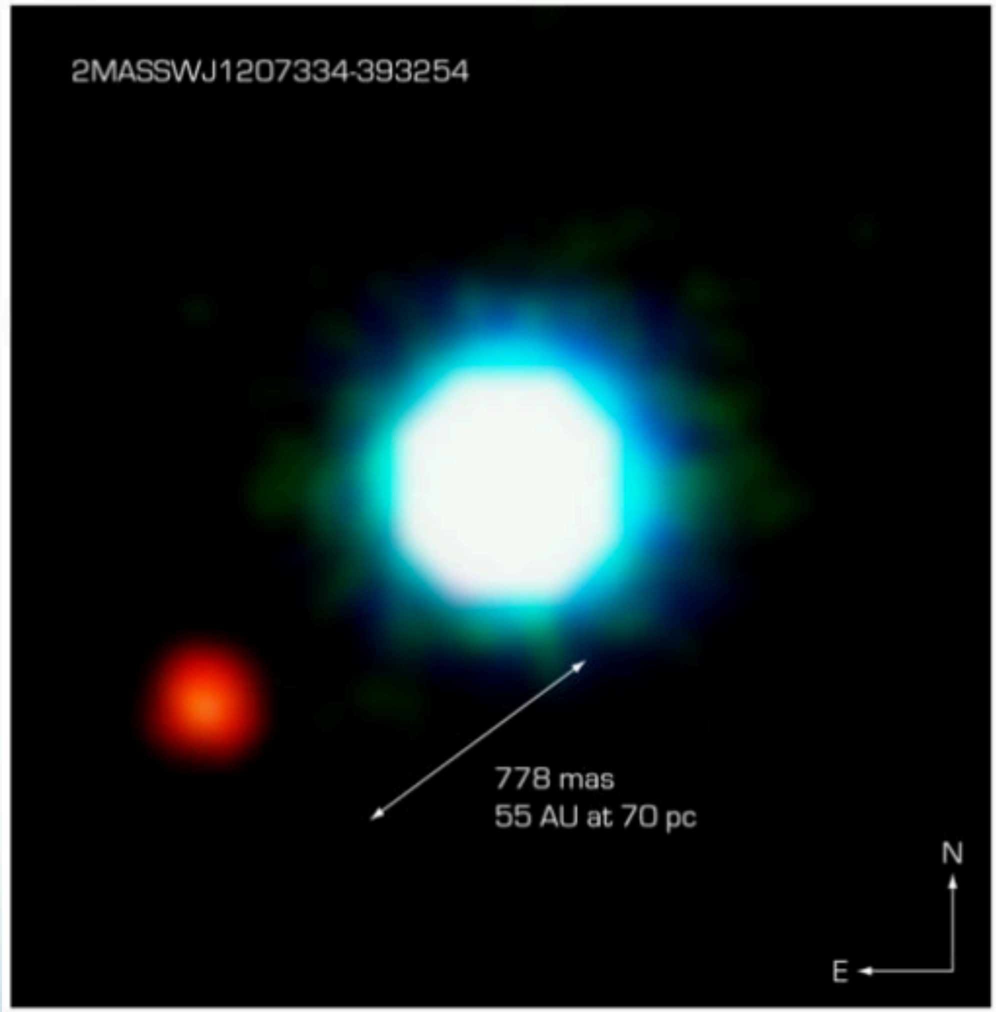
We report results of a re-analysis of archival Spitzer IRAC direct imaging surveys encompassing a variety of nearby stars. Our sample is generated from the combined observations of 73 young stars (median age, distance, spectral type = 85 Myr, 23.3 pc, G5) and 48 known exoplanet host stars with unconstrained ages (median distance, spectral type = 22.6 pc, G5). While the small size of Spitzer provides a lower resolution than 8m-class AO-assisted ground based telescopes, which have been used for constraining the frequency of 0.5 - 13 M_J planets at separations of $10 - 10^2$ AU, its exquisite infrared sensitivity provides the ability to place unmatched constraints on the planetary populations at wider separations. Here we apply sophisticated high-contrast techniques to our sample in order to remove the stellar PSF and open up sensitivity to planetary mass companions down to $5''$ separations. This enables sensitivity to 0.5 - 13 M_J planets at physical separations on the order of $10^2 - 10^3$ AU , allowing us to probe a parameter space which has not previously been systematically explored to any similar degree of sensitivity. Based on a colour and proper motion analysis we do not record any planetary detections. Exploiting this enhanced survey sensitivity, employing Monte Carlo simulations with a Bayesian approach, and assuming a mass distribution of $dn/dm \propto m^{-1.31}$, we constrain (at 95% confidence) a population of 0.5 - 13 M_J planets at separations of 100 - 1000 AU with an upper frequency limit of 9%.

Outline

- Direct Imaging Introduction
- High Contrast Imaging with Spitzer
- Results of Spitzer Imaging Survey Re-analysis
- Wide Giant Planet Population Analysis

Imaging Technique

- Resolve planet from its parent star
- Provides a wealth of information
  - All orbital elements
  - Temperature
  - Radius
  - Mass
  - Atmospheric Constituents



NACO Image of the Brown Dwarf Object 2M1207 and GPCC

Imaging – an issue of size

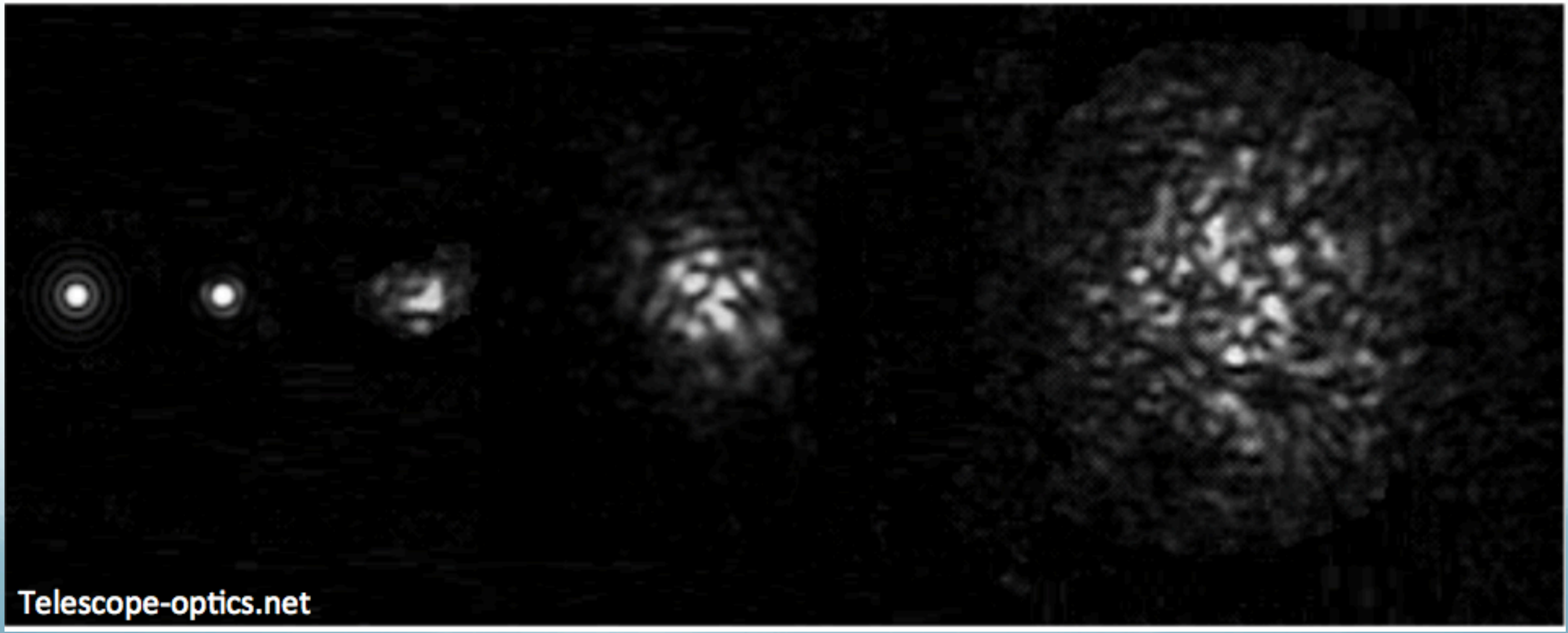
- Under ideal conditions PSF FWHM scales linearly with diffraction limited resolution λ / D

Subaru D ~ 8m

Hubble D ~ 2m

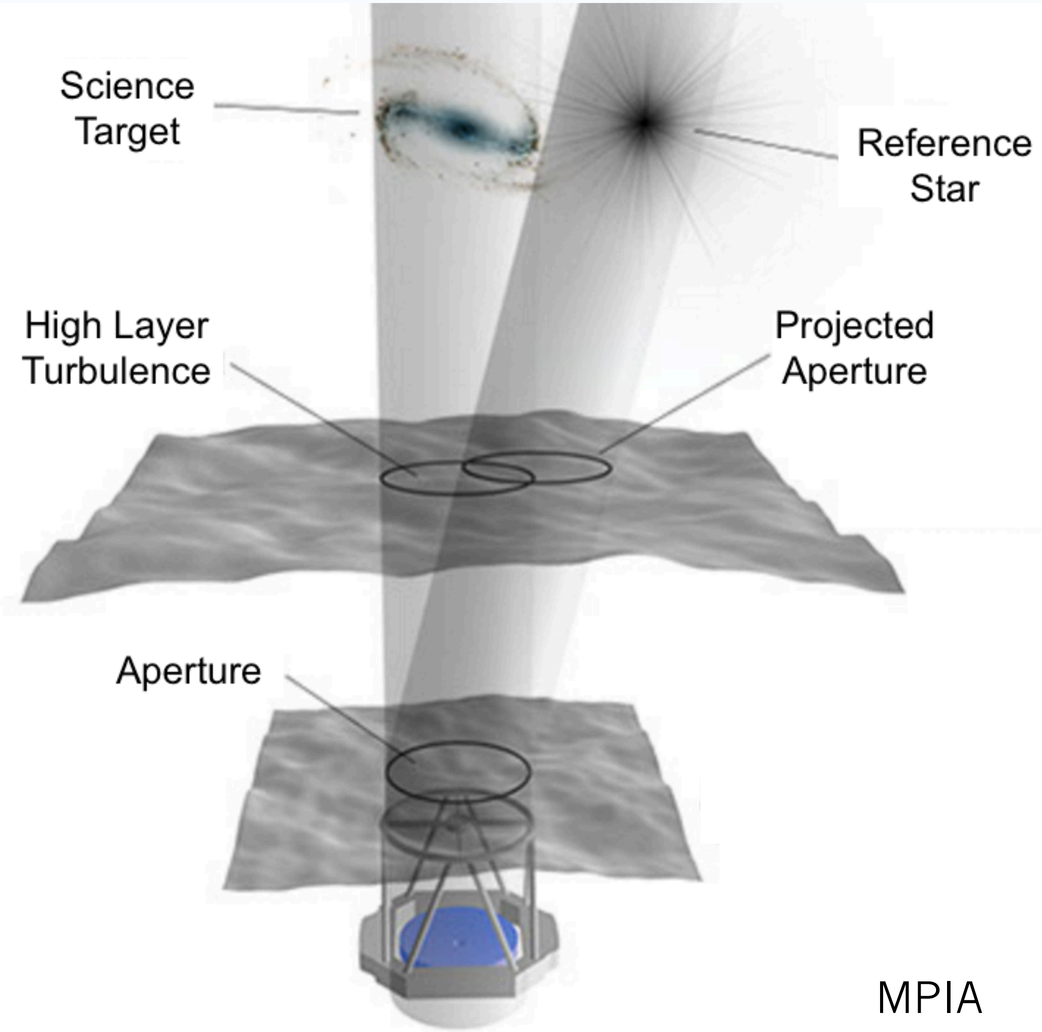
Diffraction vs Seeing Limit

- Diffraction limited FWHM scales with λ / D
  - ~ 0.05 arcsec at NIR wavelengths
- Seeing limited FWHM dependent on site and atmospheric conditions
  - ~ range of 0.5 – 3 arcsec



Adaptive Optics Caveat

- Reference star is suitably close to the target star so both wavefronts travel through the same turbulent layers and statistically experience the same distortion
- Further off-axis the wavefront distortion become less and less correlated – anisoplanatism
- Complete decorrelation reached at isoplantic angle
  - Typical values 10" – 20" in NIR
- Typical imaging instruments are restricted to this FOV



Adaptive Optics Caveat

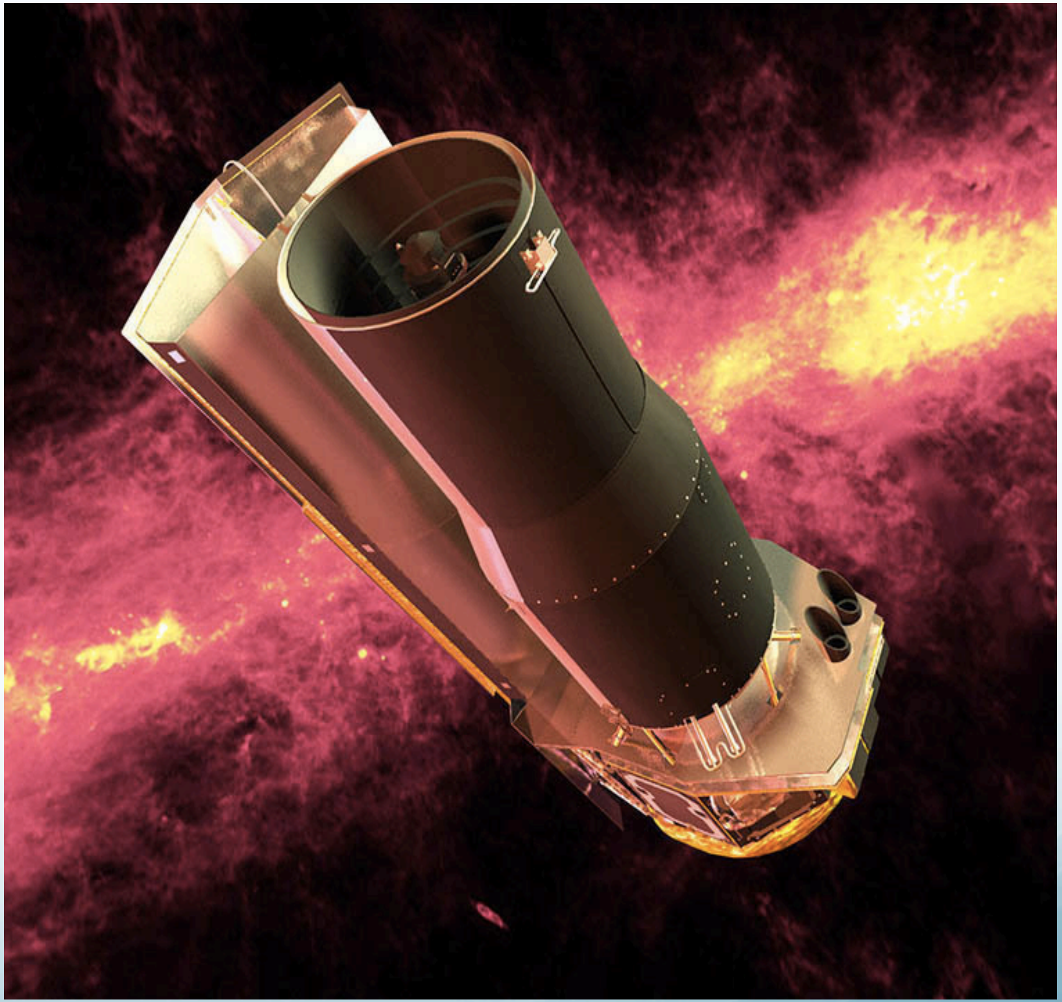
- Restricted FOV limits sensitivity to planetary mass companions at separation on the order of 10 – 100 AU
- Upper limit on planet frequency can be determined by subjecting imaging survey results to statistical analysis
- Constraining the giant planet population at 10 – 100 AU separations allows for stringent constraints to be placed on formation and evolutionary theories

Mass Range (M_J)	Separation Range (AU)	Planet Frequency Fractional Upper Limit	Study
0.5 - 13.0	50 - 250	0.093	(Lafrenière et al. 2007b)
0.5 - 13.0	25 - 100	0.110	(Lafrenière et al. 2007b)
1.0 - 20.0	10 - 150	0.060	(Biller et al. 2013)
1.0 - 13.0	40 - 150	0.100	(Chauvin et al. 2010)

Durkan et al. 2016, accepted

Spitzer Space Telescope

- IRAC 5.2’ x 5.2’ FOV
- Operates 4 channels
  - 3.6, 4.5, 5.8, 8.0 micron
- Ideal for detection of wide giant planets
- However telescope diameter = 0.85 m
- At 4.5 micron FWHM = 1.72”



NASA

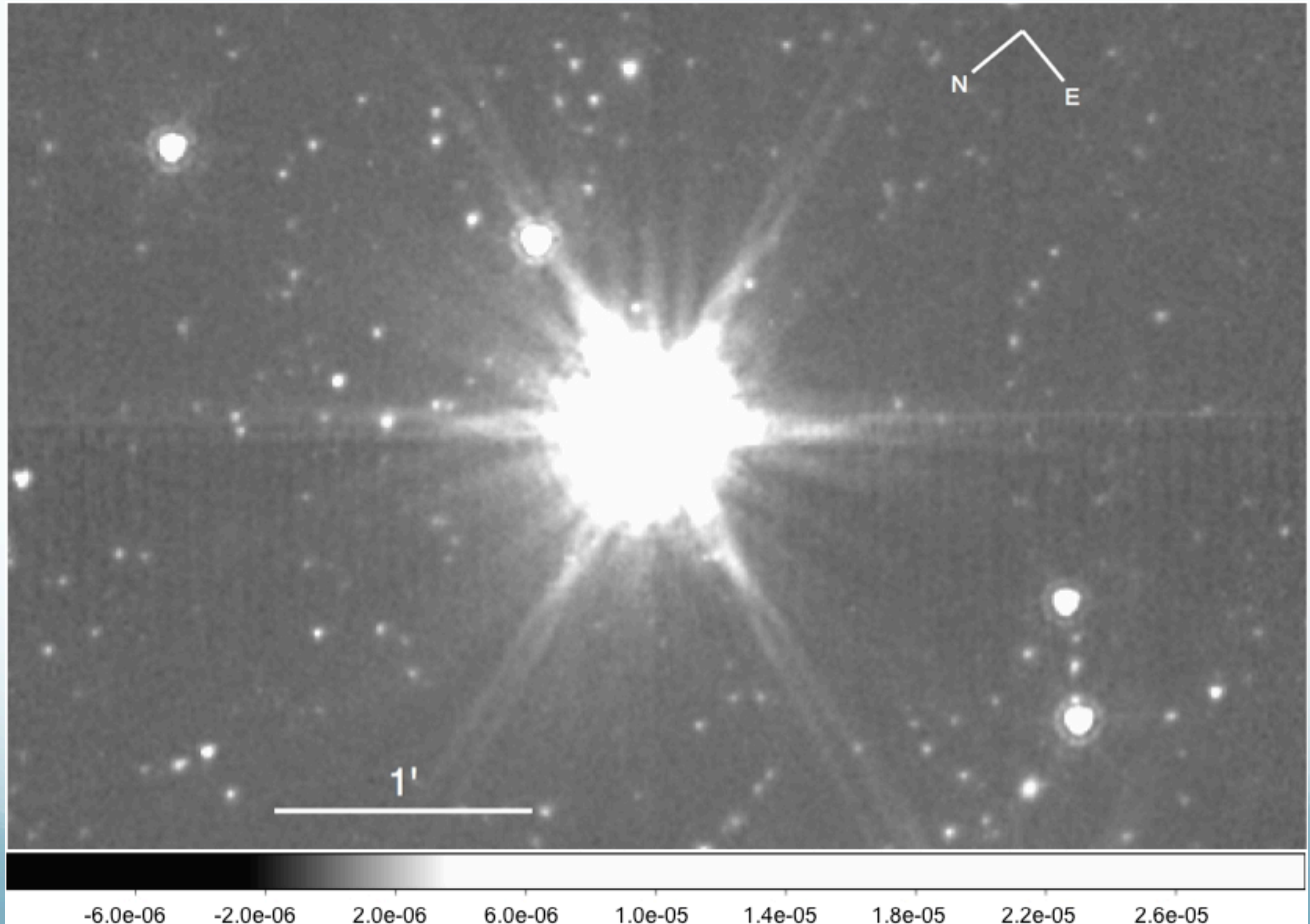
Survey Sample

- Combination of two archival Spitzer programs
- Program 34
  - Targeted 73 nearby, young targets
  - Median distance = 23.3 pc
  - Median age = 85 Myr
  - Median spectral type = G5
  - Median H band magnitude = 5.29
- Program 48
  - Targeted 48 nearby, relatively old, known exoplanet hosts
  - Median distance = 22.6 pc
  - Median age = 5.5 Gyr
  - Median spectral type = G5
  - Median H band magnitude = 4.96

PSF Subtraction

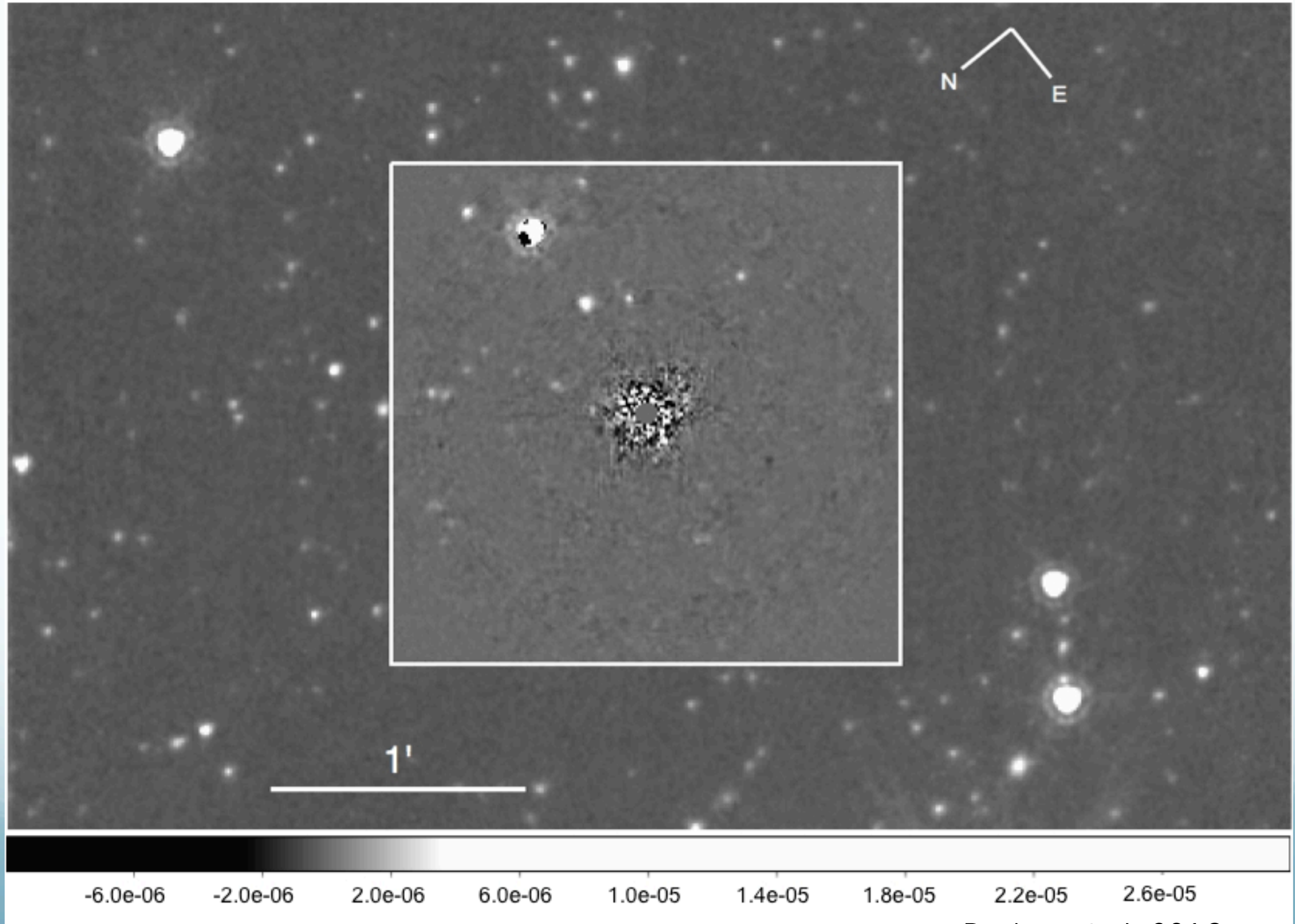
- Combined survey sample represents the library stack of available PSF's
- Conventional PSF construction is made from a mean / median of the image stack
- Optimal PSF construction can be made with sophisticated algorithms such as LOCI and PCA
- LOCI
  - Creates an optimal reference through the linear combination of library PSF's
- PCA
  - Creates an optimal reference through the linear combination of orthogonal basis sets
  - Orthogonal basis sets are the eigenvectors of the covariance matrix of the library stack
  - Principal components represent features that occur systematically throughout the data

PSF Subtraction



Durkan et al. 2016, accepted

PSF Subtraction



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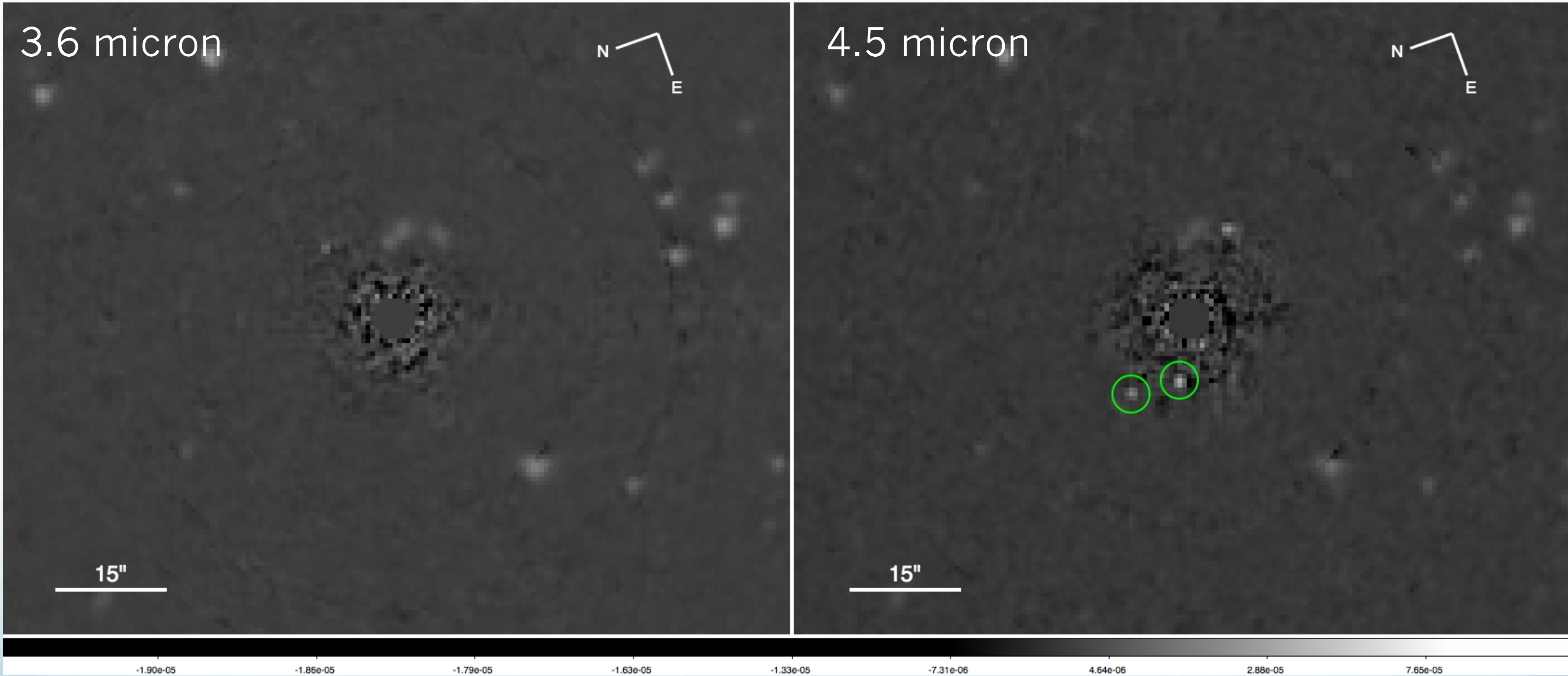
Source Candidacy



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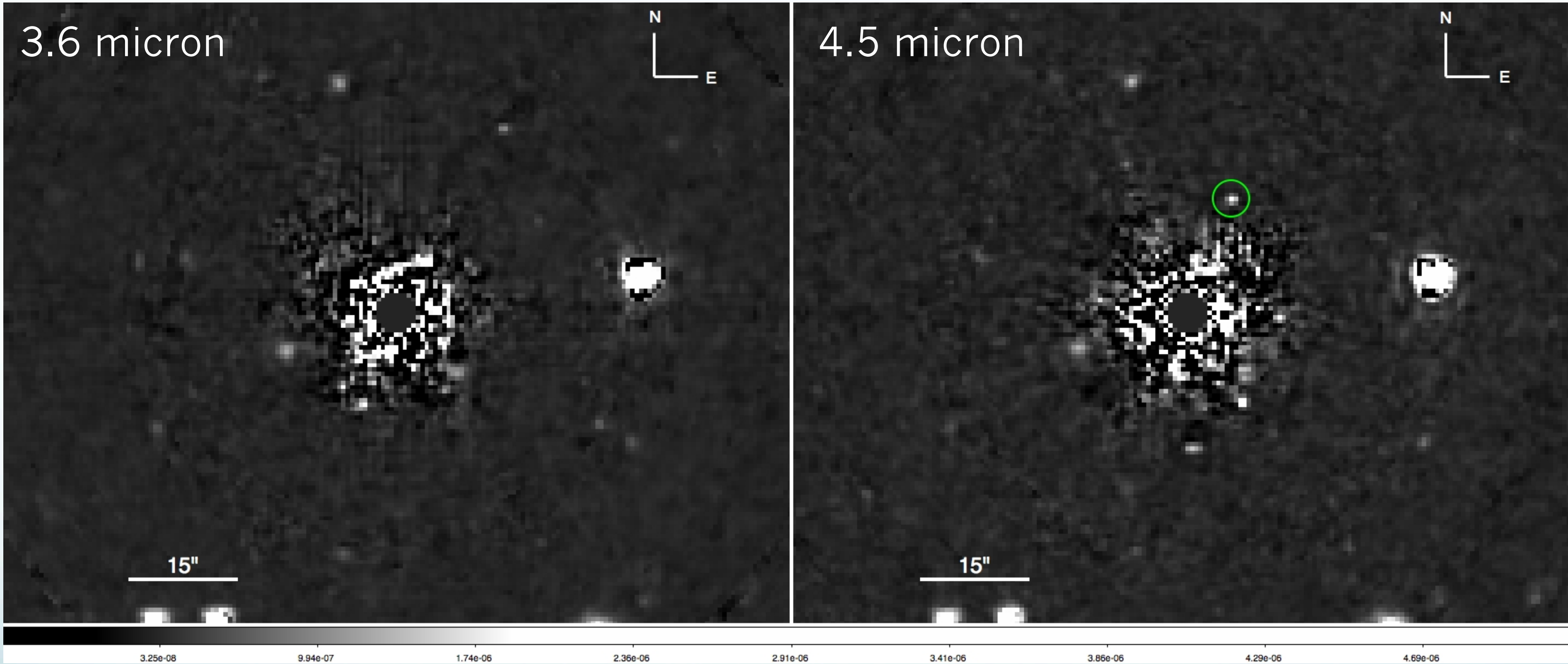

Durkan et al. 2016, accepted

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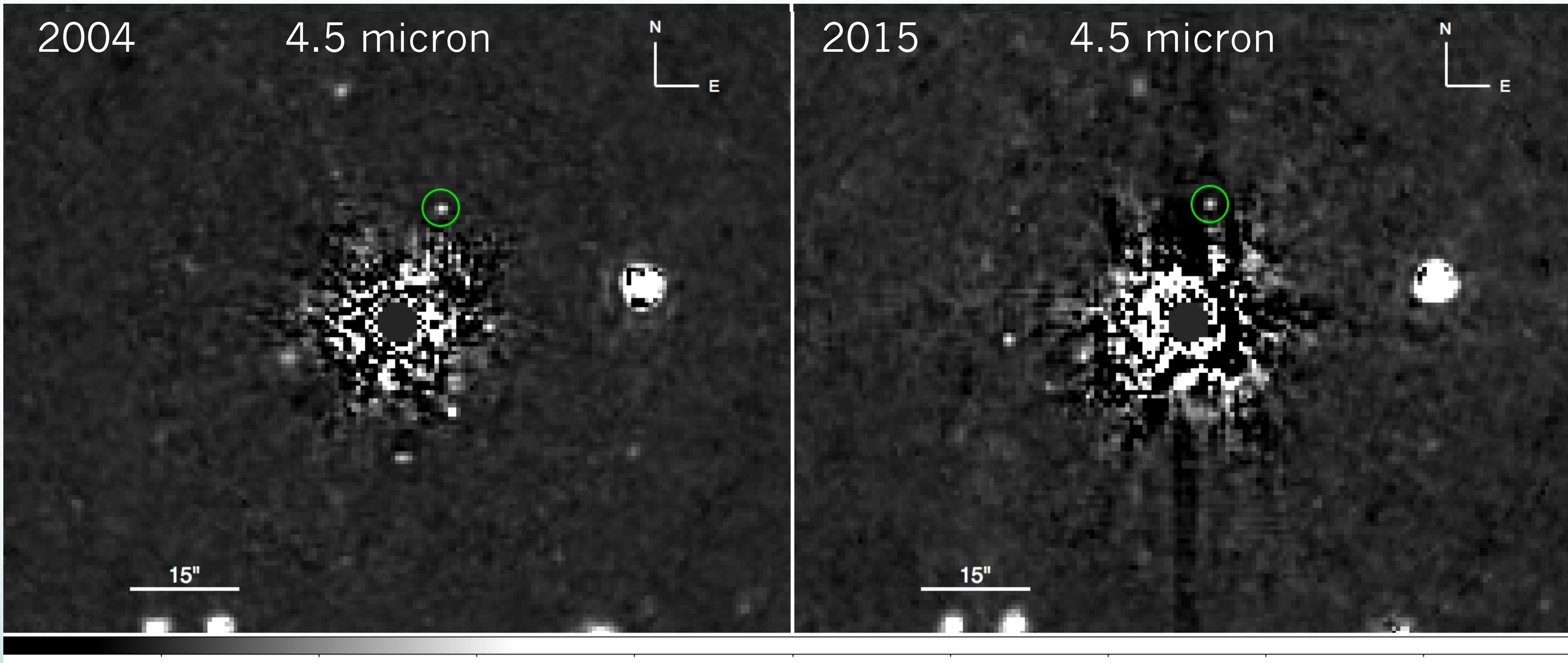
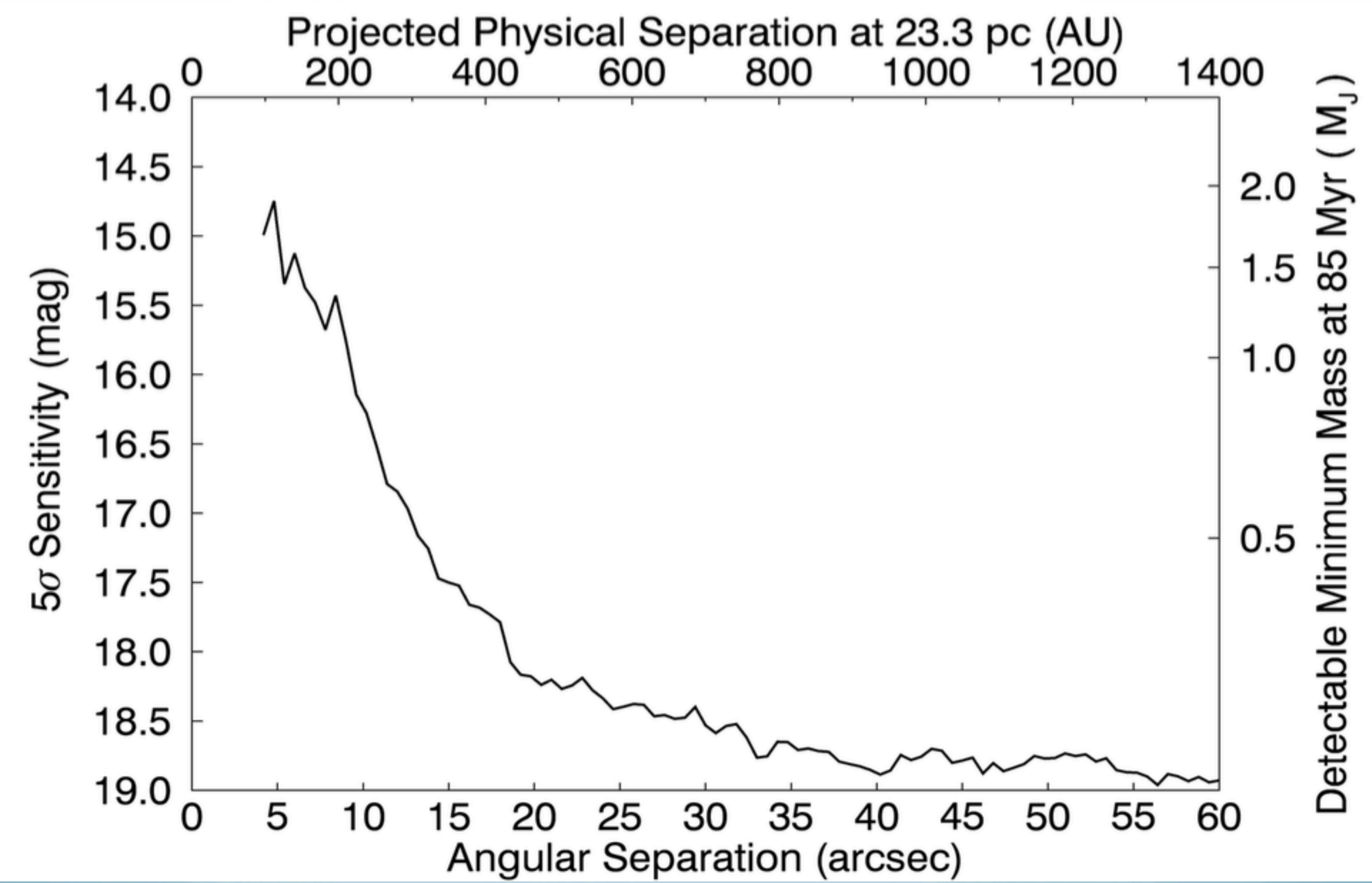


Durkan et al. 2016, accepted

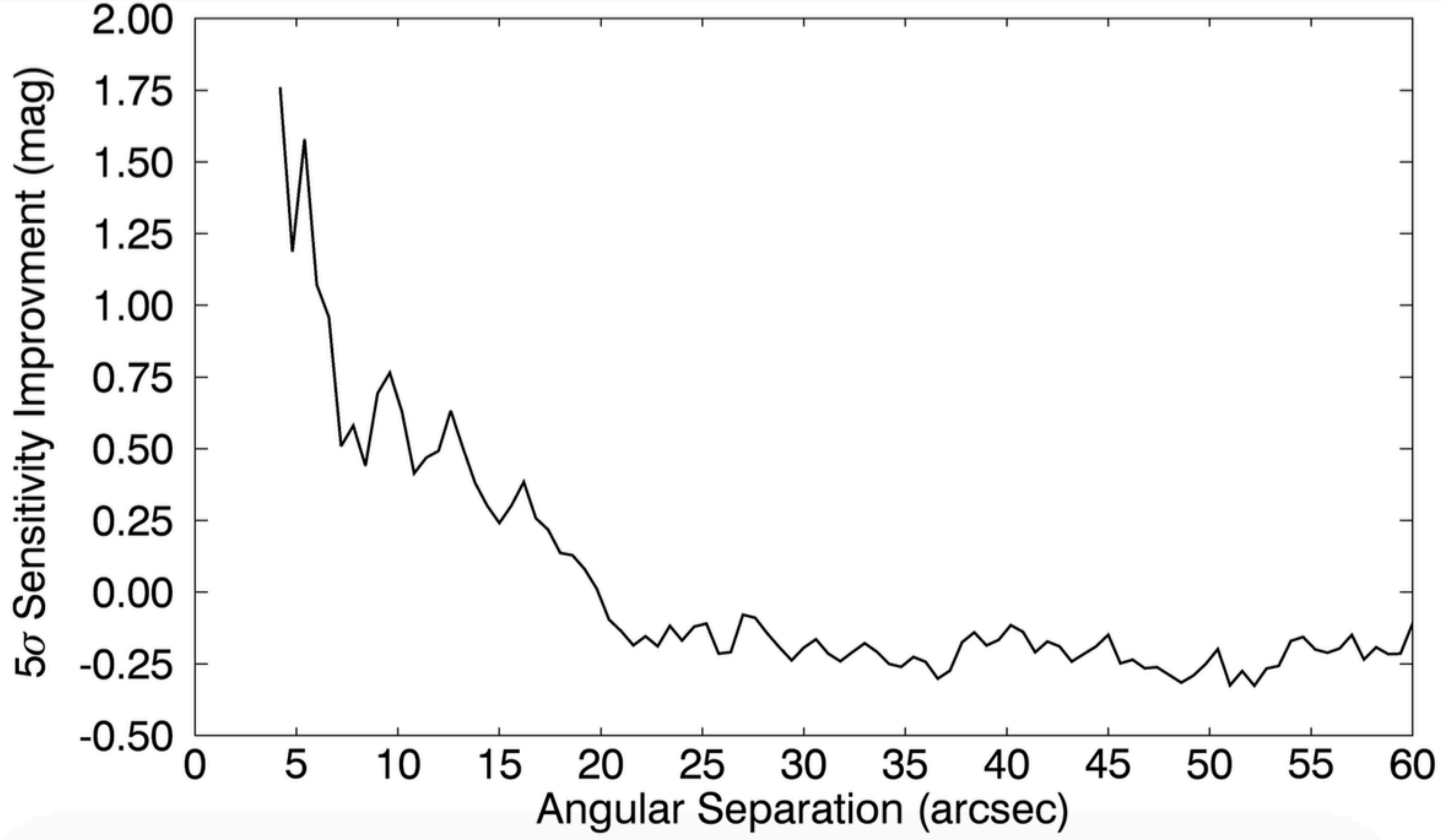
Image Sensitivity



Program 34 stars

Durkan et al. 2016, accepted

PCA Effectiveness



Durkan et al. 2016, accepted

Population Constraints

- We exploit the null detection result and the magnitude detection limits to place constraints on the wide giant population through a Bayesian analysis
- Effectively the analysis determines the population of wide giants that is consistent with the derived planet detection probability and the null survey result.
- The planet frequency is given by the Bayesian approximation;

$$f_{max} \approx -\ln(1-\alpha)/N\langle P_j \rangle$$

- We choose α to be 95%

Simulated Planetary Properties

- Simulate 10,000 planets
- Sample mass between 0.5 – 13 MJ assuming a distribution of $dn/dm \propto m^{-1.31}$
- Sample separation between 100 – 1000 AU assuming a linear distribution
- Age sampled between limits of reliable literature estimates for P34 targets, 1 – 10 Gyr for P48 targets
- Mass translated into magnitude using COND-based evolutionary models
- Detection probability given by number of detected planets / 10,000

Result

Mass Range (M_J)	Separation Range (AU)	Planet Frequency Fractional Upper Limit	Study
0.5 - 13.0	50 - 250	0.093	(Lafrenière et al. 2007b)
0.5 - 13.0	25 - 100	0.110	(Lafrenière et al. 2007b)
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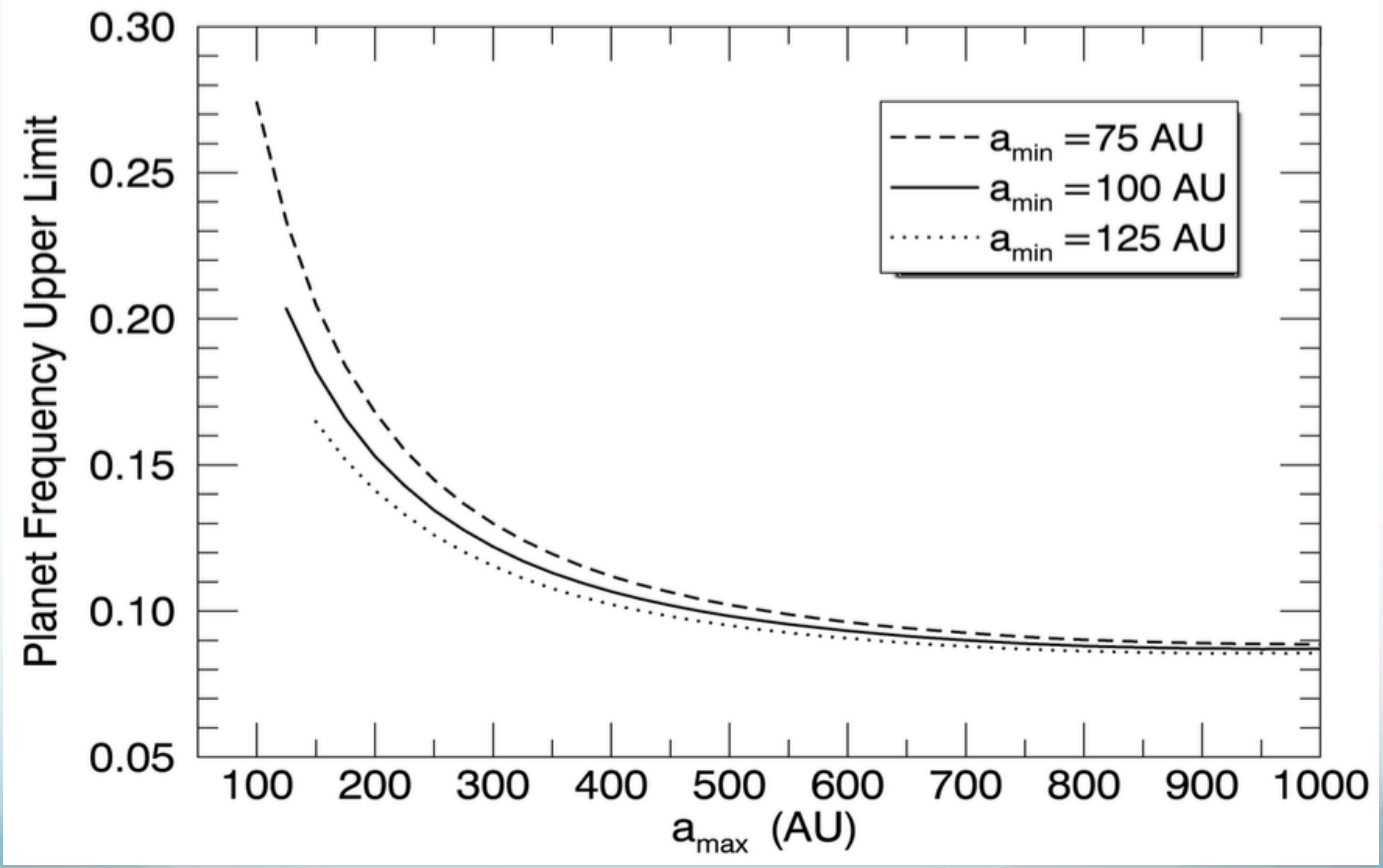
1.0 - 13.0	40 - 150	0.100	(Chauvin et al. 2010)
0.5 - 13.0	100 - 1000	0.090	(Durkan et al. 2016)

Conclusion

- Previously the large PSF associated with Spitzer has severely limited its capability for directly imaging exoplanets
- With the application of PCA we have removed the stellar PSF and opened up sensitivity to planetary mass companions over 100 – 1000 AU separations
- PCA has provided up to a magnitude sensitivity improvement with respect to conventional PSF subtraction methods
- Through the coupling of Monte Carlo simulations and a Bayesian analysis for the first time we have constrained the population of 0.5 – 13 M_J , 100 – 1000 AU planets, deriving an upper frequency limit of 9%

Supplementary Information

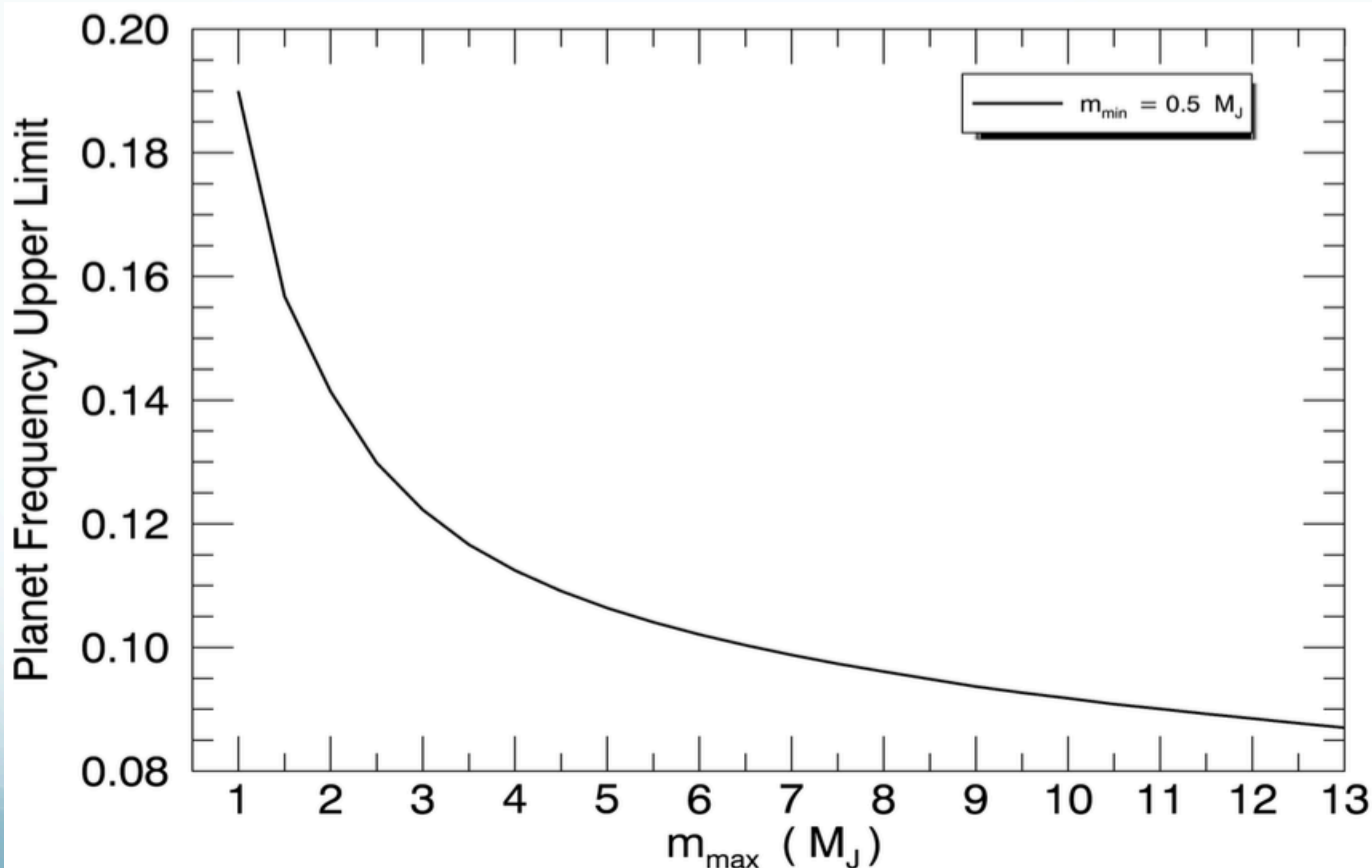
Derived Constraints



Constant mass range 0.5 – 13 M_J

Durkan et al. 2016, accepted

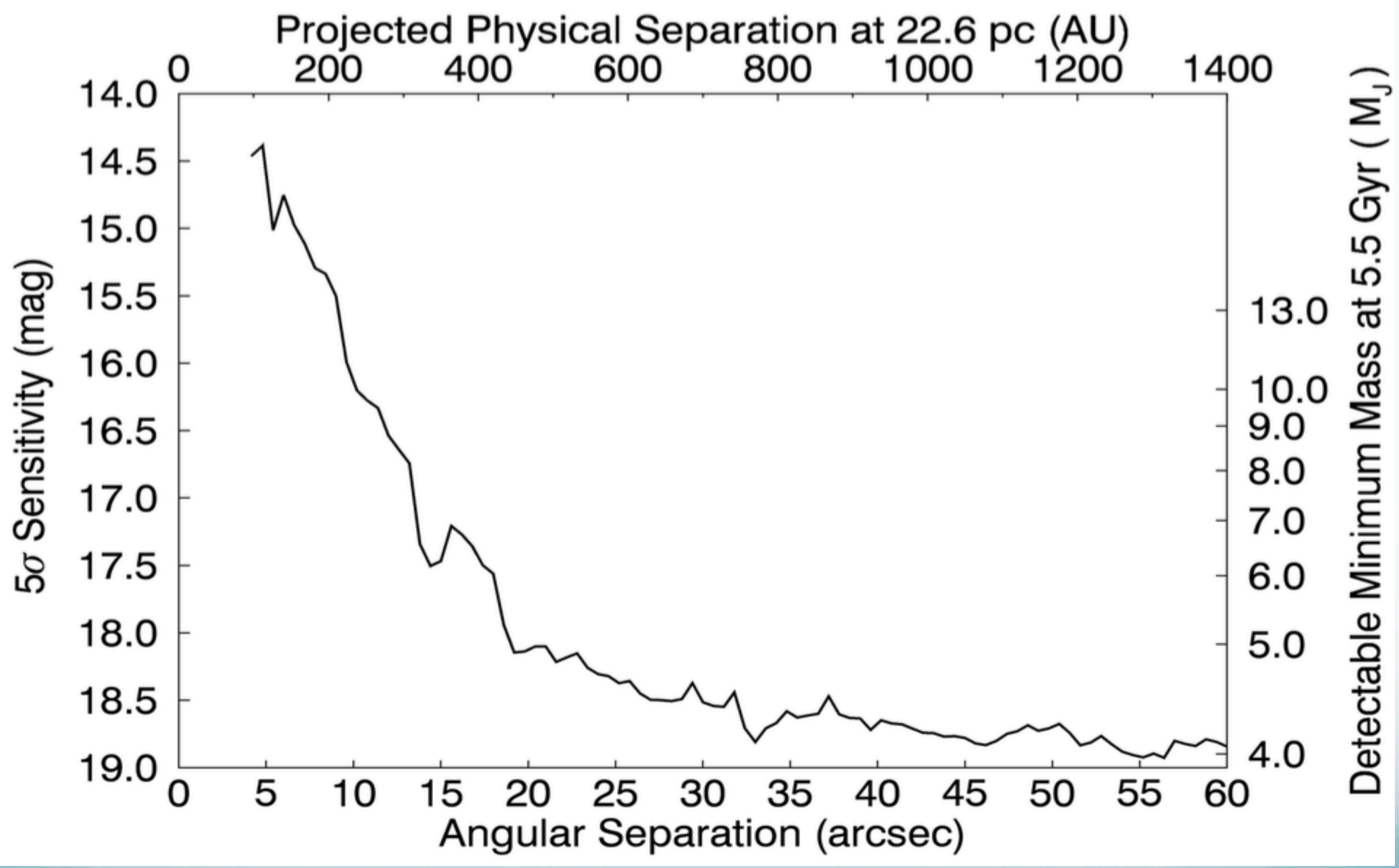
Derived Constraints



Constant separation range 100 – 1000 AU

Durkan et al. 2016, accepted

Image Sensitivity



Program 48 stars

Durkan et al. 2016, accepted

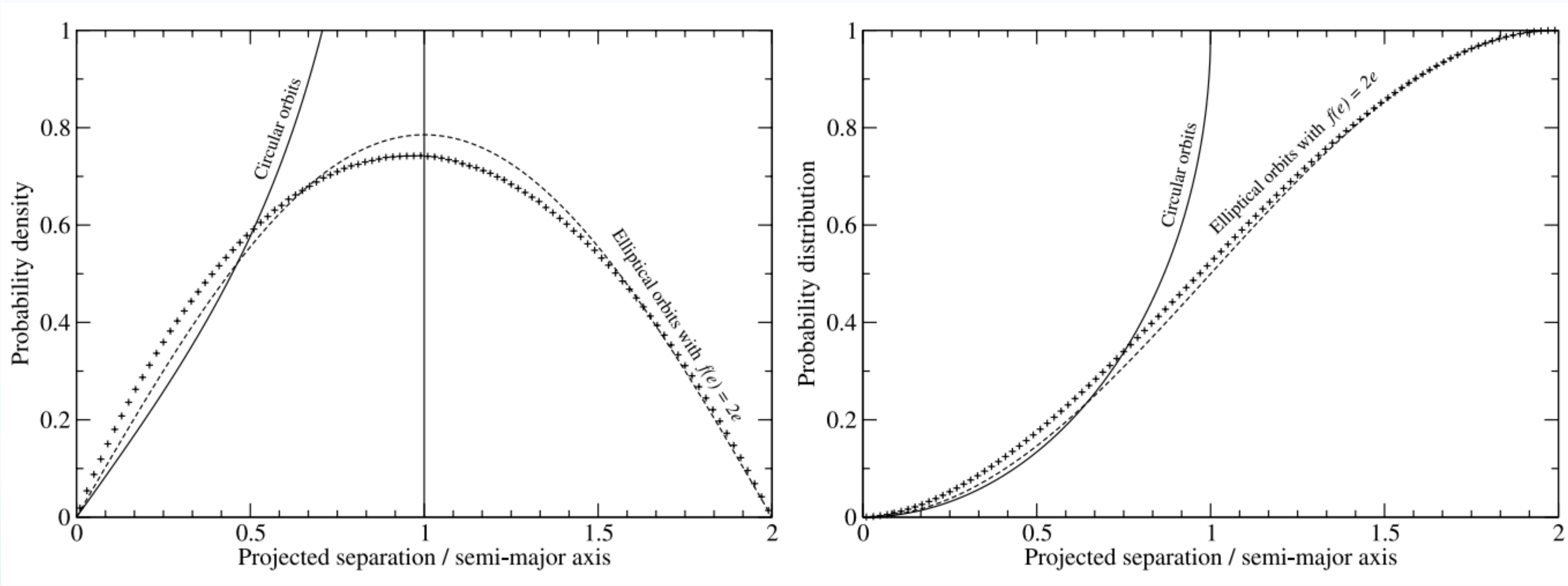
Potential Bias

- Presence of a detected short period planet for 48 stars in the sample
- Presence of 43 binary stars in the sample
  - We record a null planet detection in these systems
  - Binary companion introduces a parameter space of instability in which we would not expect a planet to orbit
  - Use stability criteria of Holman & Wiegert (1999) to determine these instability regions and ensure they are counted as non-detectable ranges when deriving probabilities
  - However an element of bias remains as true frequency of wide giants around binary stars may be different to that around single stars

Simulated Planetary Properties

- Simulate 10,000 planets
- Sample mass between 0.5 – 13 MJ assuming a distribution of dn/dm α $m^{-1.31}$
- Sample separation between 100 – 1000 AU assuming a linear distribution
- Sample orbital projection factor using method of Brandeker et al. 2006
- Physical separation is translated to angular separation using known stellar distance
- Age sampled between limits of reliable literature estimates for P34 targets, 1 – 10 Gyr for P48 targets
- Mass translated into magnitude using COND-based evolutionary models
- Each simulated planet is then mapped onto the sensitivity curve and detection / non-detection is recorded
- Detection probability given by number of detected planets / 10,000

Simulated Planetary Properties



$S = 2\pi^{-1}\arccos(1 - 2X)$

Brandeker et al. 2006