State-of-the Art of Demographics Study in Direct Imaging

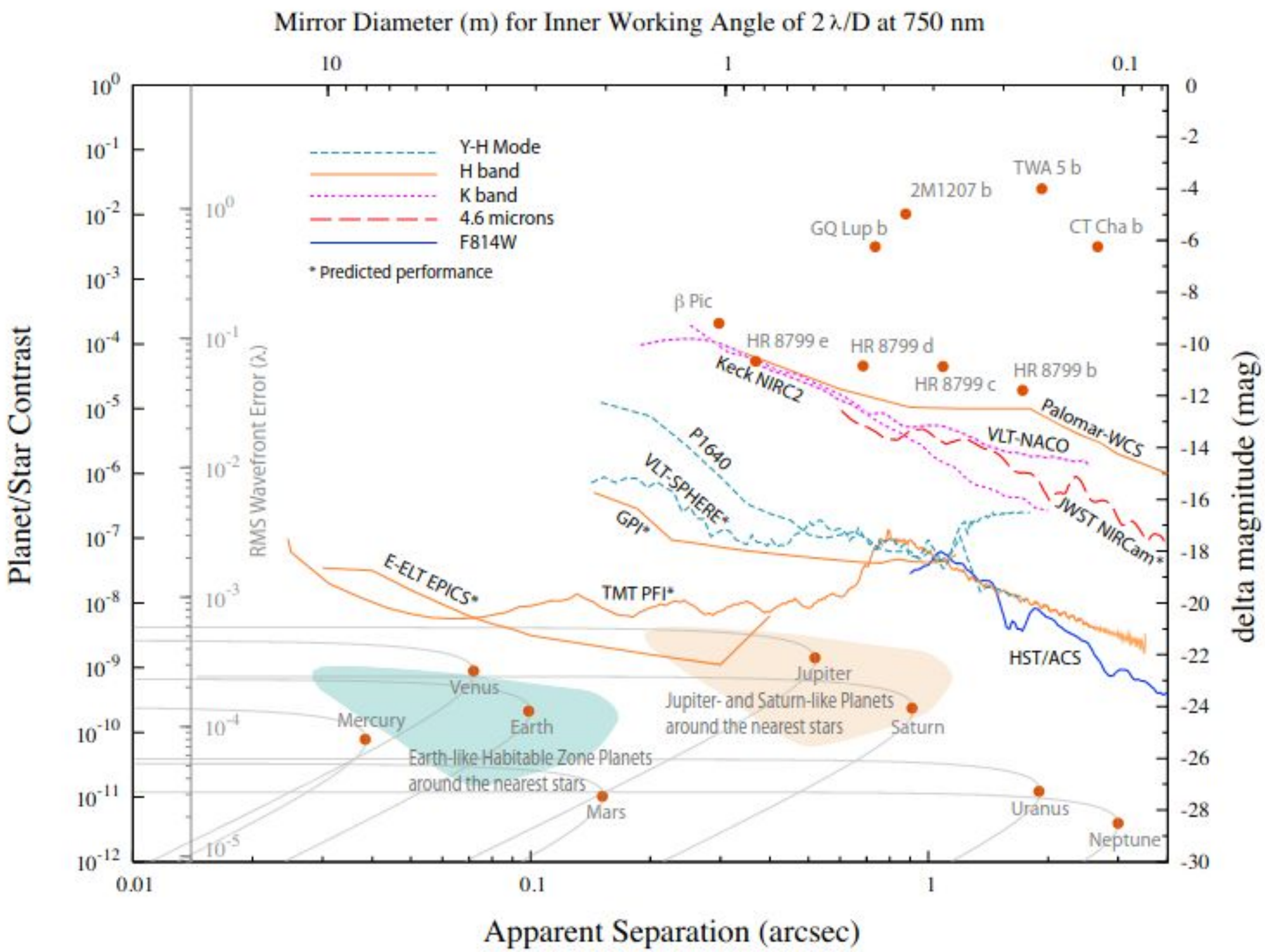
Outline

Demographics Studies in DI

1. Introduction to early DI surveys,
2. First Statistical Studies,
3. Designing the SHINE Survey,
4. SHINE-F150 Demographics Study,
5. Lessons learned & perspectives

1. Introduction to early DI surveys

Typical planet–star contrast are about:



1. Introduction to early DI surveys

Young Stars near the Sun

- 1983. TW Hya, isolated T Tauri star (Rucinski & Krautter 1983)

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- 2012. About 10 new associations
  - (TWA, β Pic, AB Dor, Tuc/Hor, η Cha, e Cha, Carina, Columba...)
  - Today, 500+ known young (<100 Myr) & nearby (<100 pc) stars

- 2018. Unveiling low-mass members, nearby Moving Groups with Gaia DR2/3

- Extension to 2000+ young stars up to 200 pc:
  - Intermediate-old (< 1.0 Gyr), nearby Moving Groups,
    - (Castor, Herculis-Lyra, Argus, Octantis)
  - Younger, but distant regions (Sco-Cen region)

- Age & membership diagnostics: isochrone, (Li, H_α), X-ray, kinematics...
  Zuckerman, Song et al.; Torres, de la Reza et al.; Mamajek et al.; Montes et al.
  Shkolnik et al.; Gagné et al.

1. Introduction to early DI surveys

Early surveys

Reference	Telescope	Instr.	Mode	Filter	FoV (as)	#	SpT	Age (Myr)
Nakajima+94	Palomar	AOC	Cor-I	$I-band$	60	24	GKM	Field
...								
Chauvin+03	ESO3.6m	ADONIS	Cor-I	H, K	13	29	GKM	$\lesssim 50$
Neuhäuser+03	NTT	Sharp/Sofi	Sat-I	K/H	33	23/10	A–M	$\lesssim 50$
Lowrance+05	*HST*	NICMOS	Cor-I	H	19	45	A–M	$10-600$
Masciadri+05	VLT	NaCo	Sat-I	H, K	14	28	KM	$\lesssim 200$
Biller+07	VLT/MMT	NaCo/ARIES	SDI	H	5	45	GKM	$\lesssim 300$
Kasper+07	VLT	NaCo	Sat-I	L'	28	22	GKM	$\lesssim 50$
Lafrenière+07	Gemini-N	NIRI	Sat-ADI	H	22	85	FGK	10-5000
Apai+08	VLT	NaCo	SDI	H	3	8	FG	12-500
Chauvin+10	VLT	NaCo	Cor-I	H, K	28	88	B-M	$\lesssim 100$
Heinze+10ab	MMT	Clio	Sat-ADI	L', M	15.5	54	FGK	100-5000
Janson+11	Gemini-N	NIRI	Sat-ADI	H, K	22	15	BA	20-700
Vigan+12	Gemini-N/VLT	NIRI	Sat-ADI	H, K	22/14	42	AF	10-400
Delorme+12	VLT	NaCo	Sat-ADI	L'	28	16	M	$\lesssim 200$
Rameau+13c	VLT	NaCo	Sat-ADI	L'	28	59	AF	$\lesssim 200$
Yamamoto+13	Subaru	HiCIAO	Sat-ADI	H, K	20	20	FG	125 ± 8
Biller+13	Gemini-S	NICI	Cor-ASDI	H	18	80	B-M	$\lesssim 200$
Nielsen+13	Gemini-S	NICI	Cor-ASDI	H	18	70	BA	50-500
Wahhaj+13	Gemini-S	NICI	Cor-ASDI	H	18	57	A-M	~ 100
Janson+13	Subaru	HiCIAO	Sat-ADI	H	20	50	A-M	$\lesssim 1000$
Brandt+14	Subaru	HiCIAO	Sat-ADI	H	20	63	A-M	$\lesssim 500$
Chauvin+15	VLT	NaCo	Sat-ADI	H	14	86	FGK	$\lesssim 200$
Meshkat+15ab	VLT	NaCo	APP-ADI	L'	28	20	AF	$\lesssim 200$
Bowler+15	Keck/Subaru	NIRC2/HiCIAO	Cor-ADI	H	10/20	78	M	$\lesssim 200$
Galicher+16	Keck	NIRC2	Cor-ADI	H, K	10	229	A-M	$\lesssim 200$
	Gemini-N/S	NIRI/NICI						
Durkan+16	*Spitzer*	IRAC	I	$4.5\,\mu m$	312	73	A-M	$\lesssim 200$

1. Introduction to early DI surveys

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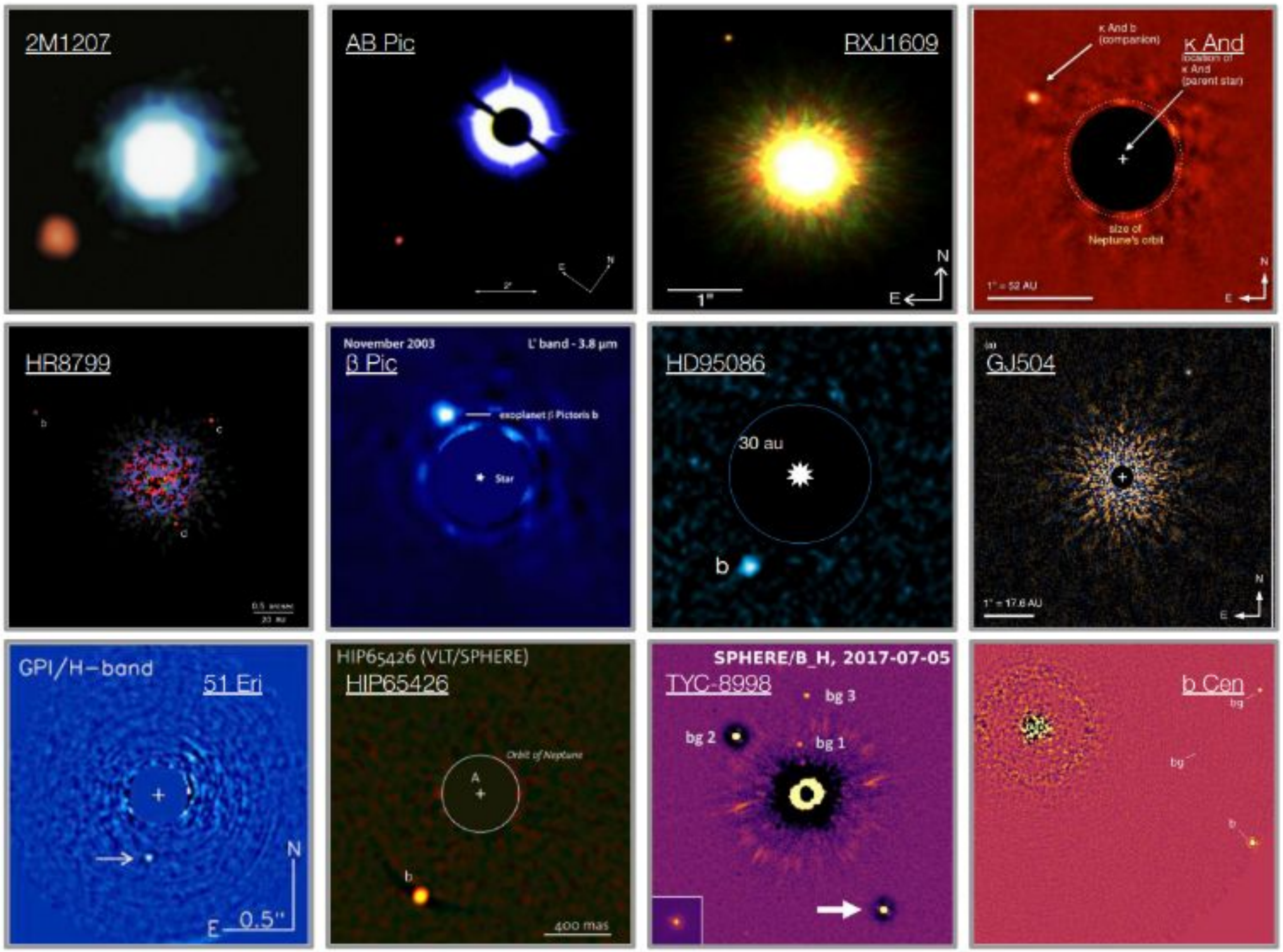
		Gemini-N/S	NIRI/NICI							
	Durkan+16	*Spitzer*	IRAC	I	4.5 μm	312	73	A-M	$\lesssim 200$	
GPIES	**Macintosh et al.**	**Gemini-S**	**GPI**	**ALC-ASDI**	**JHK**	**3.5**	**500**	**A-M**	**1 - 1000**	***started 2014***
SHINE	**Chauvin et al.**	**VLT**	**SPHERE**	**ALC-ASDI**	**JHK**	**12**	**500**	**A-M**	**1 - 1000**	***started 2015***

1. Introduction to early DI surveys

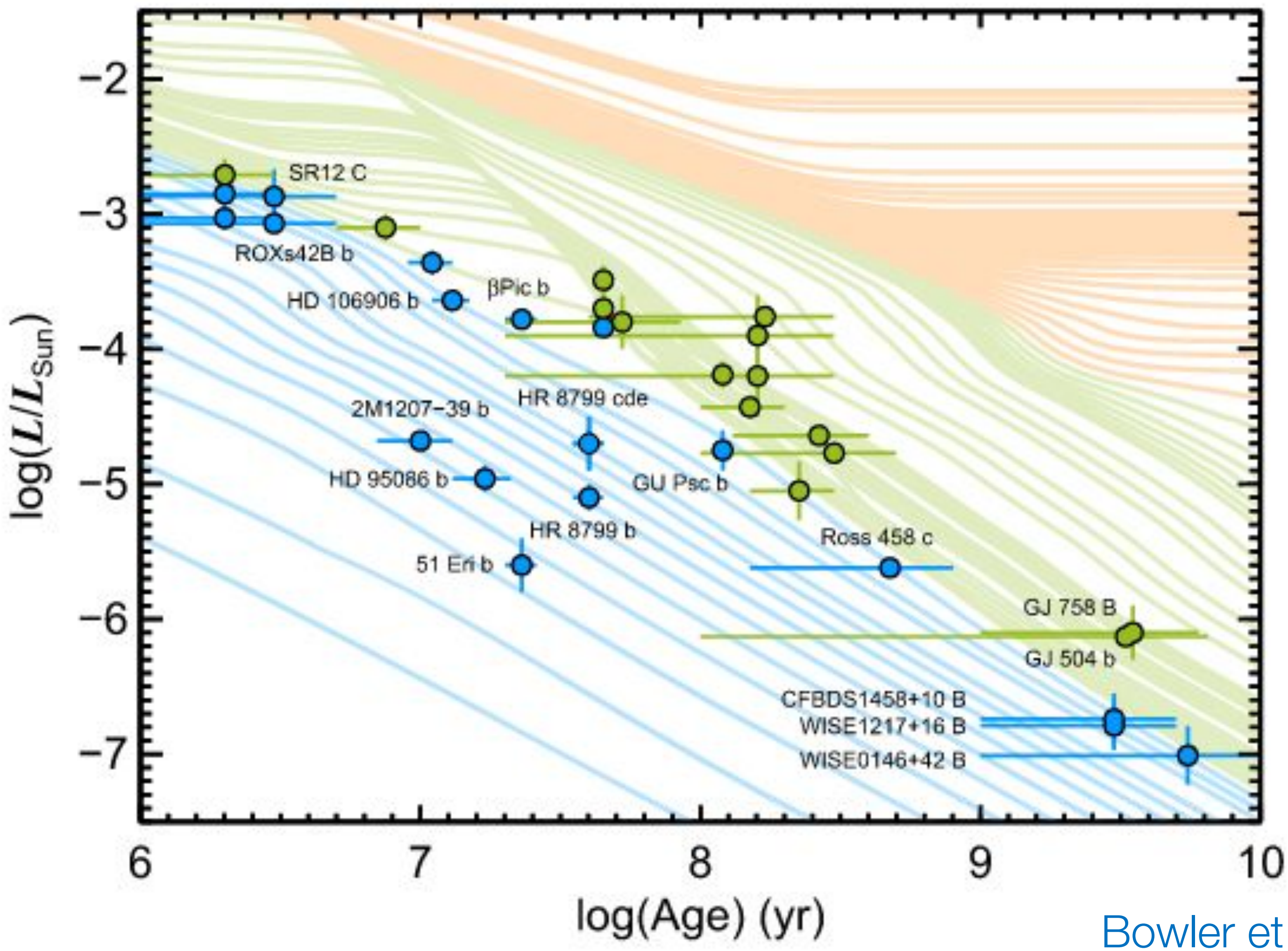
Leading to key discoveries…



1. Introduction to early DI surveys

Leading to key discoveries…

- Exploration of new parameter space: mass, radius, temperature…

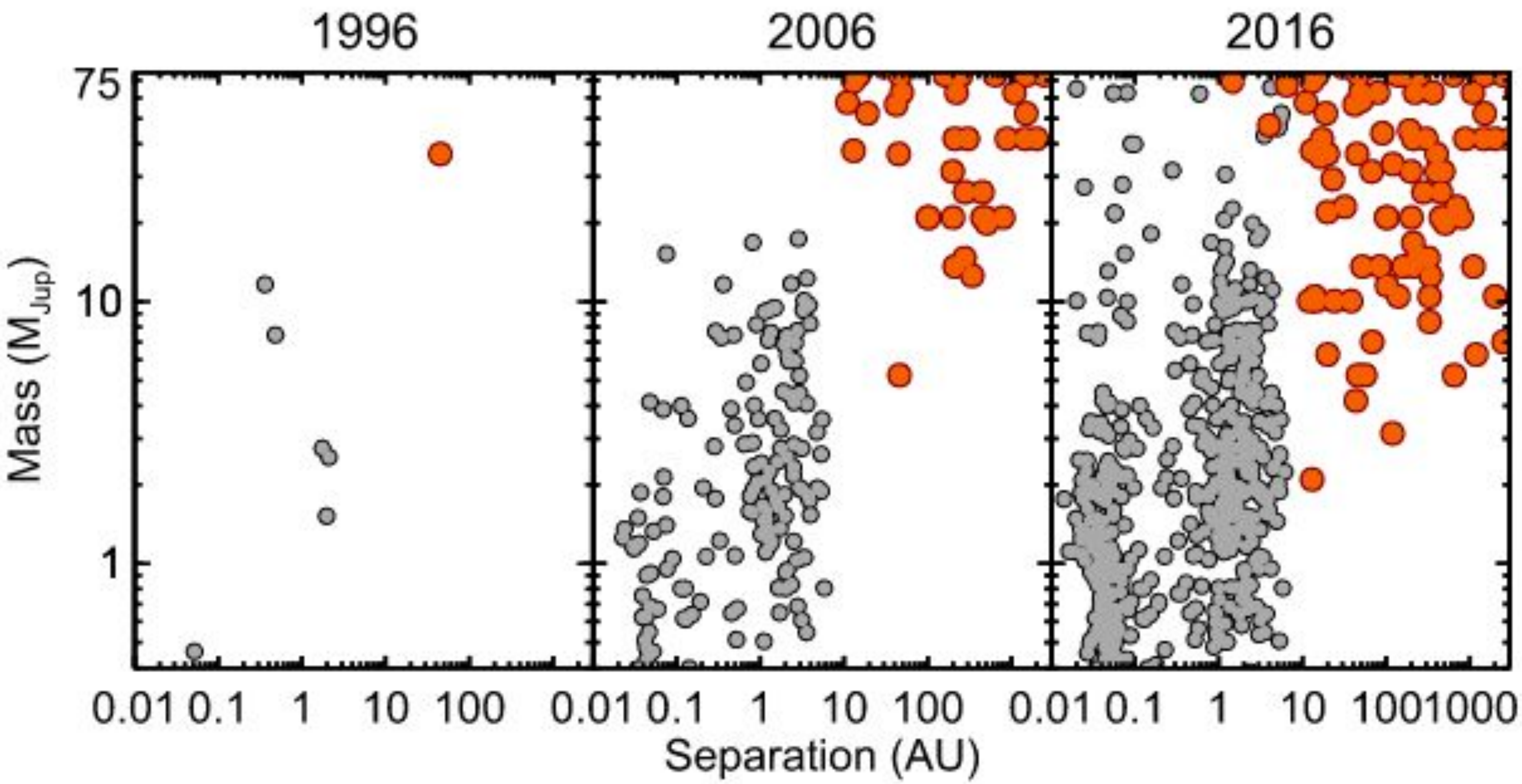


Bowler et al. (2016)

1. Introduction to early DI surveys

Leading to key discoveries… but rare…

- Limited to high-mass ratio/wide orbit planetary-mass companions in the early days
- Various surveys reporting non-detection

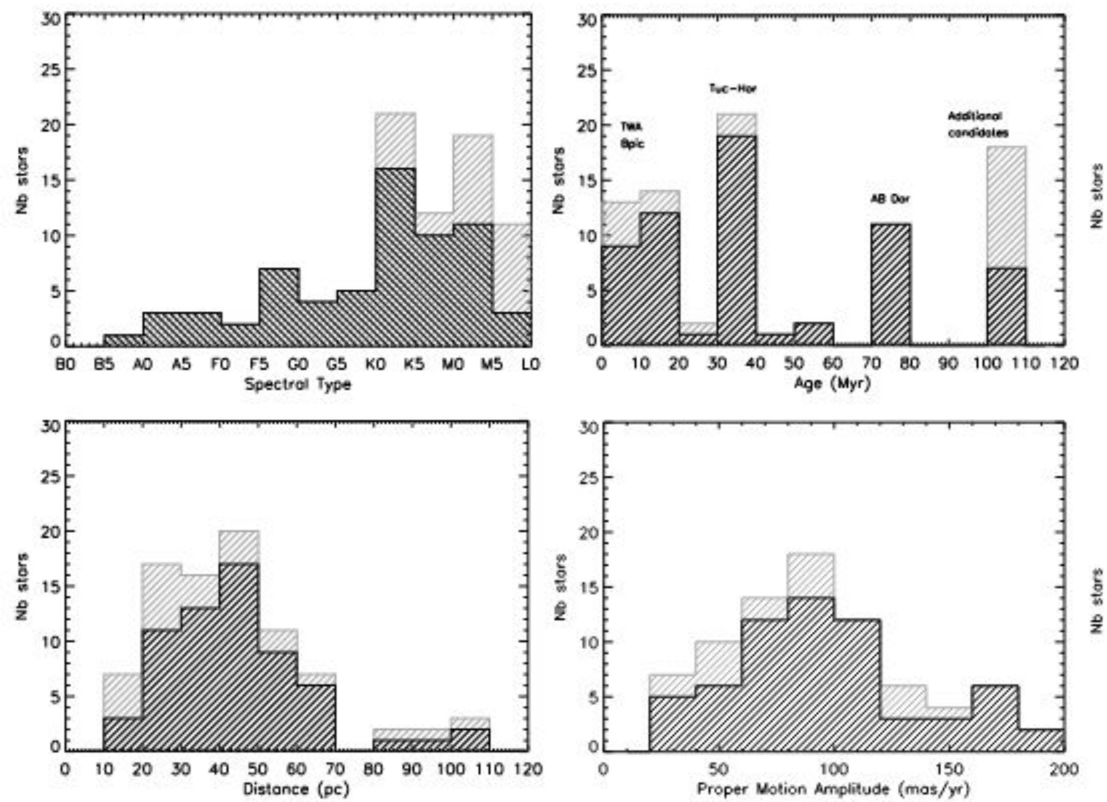


Bowler et al. (2016)

2. First Statistical Studies (<2010)

Various key limitations

- Inhomogeneous & small samples,
- Non-detection,
- No demographics predictions from planet formation theories (population synthesis)
- Unique reference: RV studies & speculation on extrapolation beyond 3 au



88 stars BAFGKM
7 years of VLT/NaCo
No differential imaging

Chauvin et al. (2010)

2. First Statistical Studies (<2010)

Various key limitations

Nielsen et al. (2008)

- Assuming "crazy" simple power-law distributions of mass and semimajor axis of giant planets for what we could not see:

$dN/dM \propto M^{\beta}$, $dN/da \propto a^{\alpha}$, and a_{cutoff}

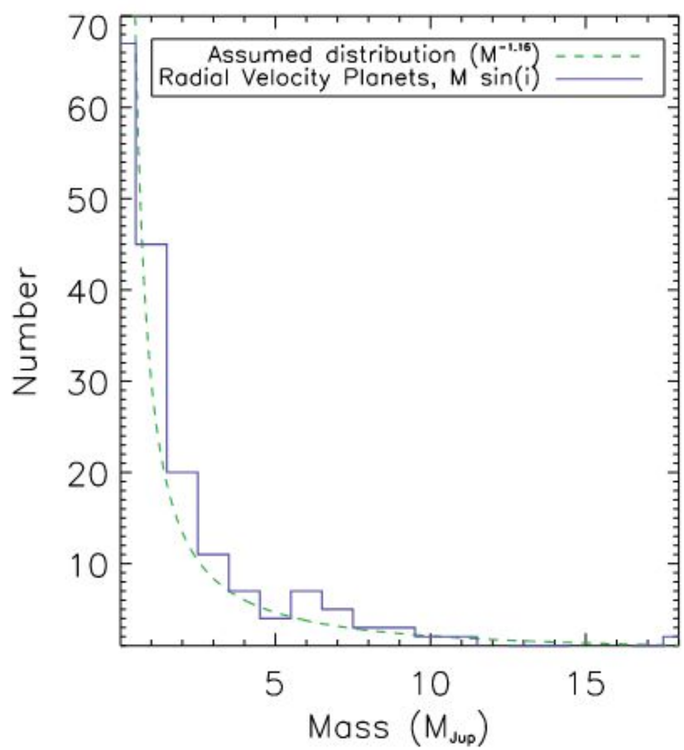


FIG. 5.—Assumed mass distribution of extrasolar planets, plotted against the histogram of known planets detected by the radial velocity method. Throughout this paper we adopt a power law of the form $dN/dM \propto M^{-1.16}$, as suggested by Butler et al. (2006), which does a reasonable job fitting the data.

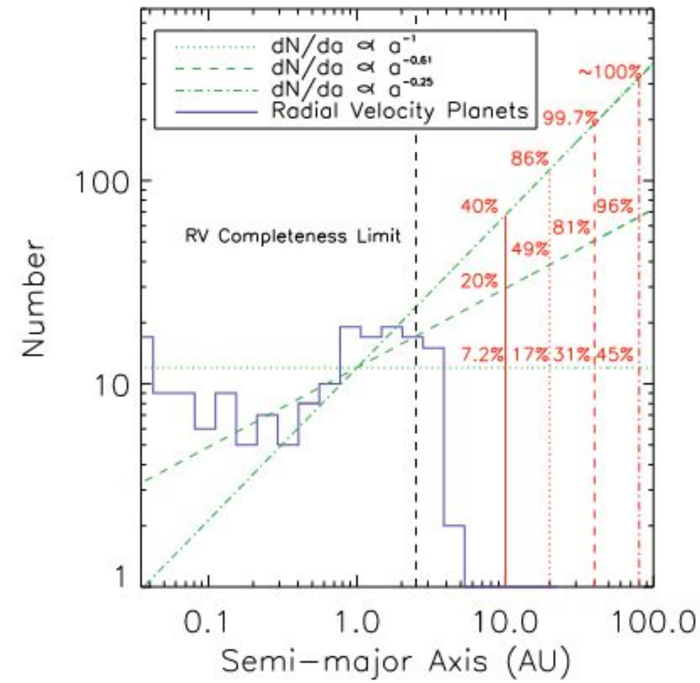


FIG. 16.—Histogram (*in blue*) of the distribution of known extrasolar giant planets found with the radial velocity method, plotted against a series of power laws considered in Fig. 14 and 15. Since radial velocity observations are only complete to about 2.5 AU, a less steep drop-off of planets with semimajor axis is possible. We give the confidence with which we can rule out various combinations of power-law index and upper cutoff (*the percentages in red*), for indices of −1, −0.61, −0.25, and upper cutoffs of 10, 20, 40, and 80 AU. While we have insufficient statistics to place strong constraints on the power law of index −1, we can rule out the other two with increasing confidence as larger values of the upper limit are considered. For example, a power law of the form $dN/da \propto a^{-0.25}$ must cutoff at 26 AU (95% confidence), while the most likely power law of index −0.61 must have its cutoff at 75 AU (also at the 95% confidence level).

2. First Statistical Studies (<2010)

Various key limitations

- Assuming “crazy” simple power-law distributions of mass and semimajor axis of giant planets for what we could not see:

$dN/dM \propto M^{\beta}$, $dN/da^{\alpha} \propto a$, and a_{cutoff}

20 stars FGKM
VLT/NaCo - Lband
No detection
Fixed β = -1.2 (Butler et al. 2006)

Kasper et al. (2007)

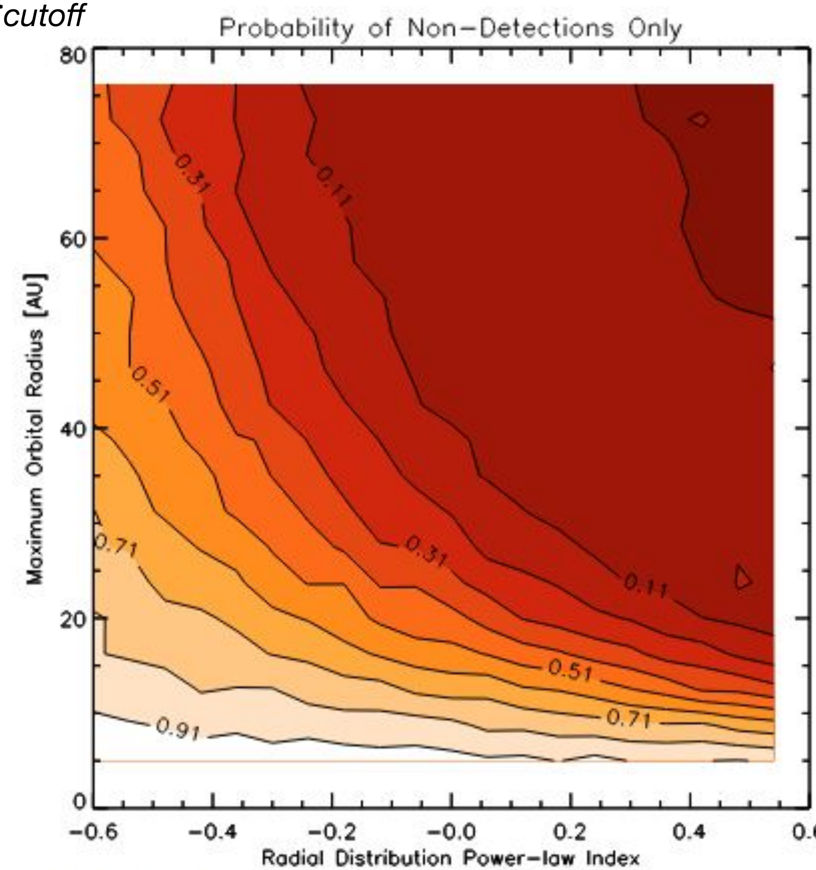


Fig. 9. Map of probability that the planet population simulated for a given α and r_{max} value is consistent with the nondetections in our survey.

2. First Statistical Studies (<2010)

Various key limitations

- Assuming "crazy" simple power-law distributions of mass and semimajor axis of giant planets for what we could not see:

$$dN/dM \propto M^{\beta},\ dN/da^{\alpha} \propto a, \text{ and } a_{cutoff}$$

79 stars FGKM
Gemini Survey - No detection

Bayesian formalism to express
the upper limit on the planet frequency
for given planet & mass distributions

Lafrenière et al. (2007)

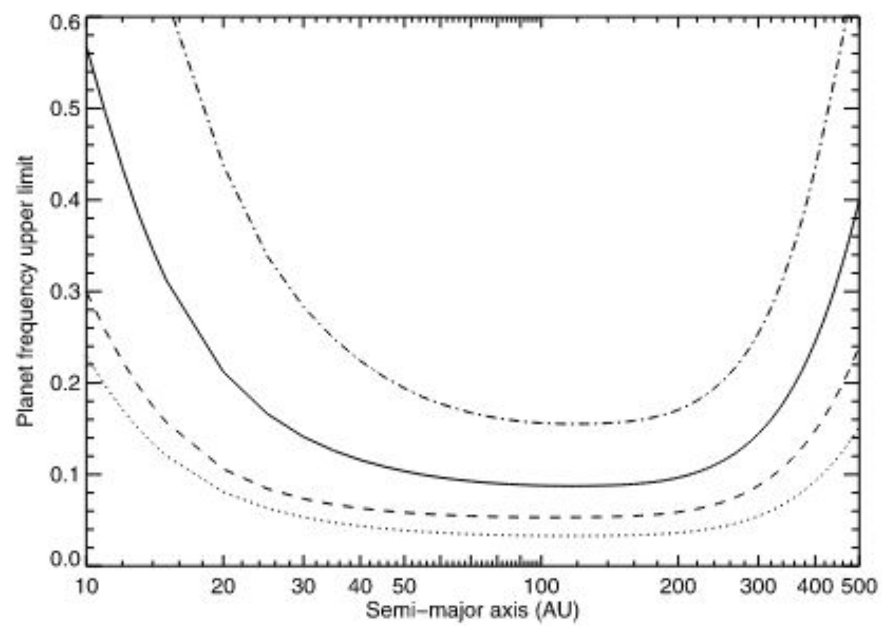


Fig. 11.—Upper limits, with a credibility of 95%, on the fraction of stars harboring at least one planet of mass in the range [0.5, 13] M_J, assuming $dn/dm \propto m^{\beta}$, and semimajor axis in various ranges. The values of β are −2 (*dot-dashed line*), −1.2 (*solid line*), and 0 (*dashed line*). For any interval, $[a_{min}, a_{max}]$ AU, of semimajor axis selected, the correct value of f_{max} to read from the graph is the maximum of the line within that interval. The 67% credibility curve for $\beta = -1.2$ is also shown (*dotted line*).

2. First Statistical Studies (<2010)

Various key limitations

- Assuming “crazy” simple power-law distributions of mass and semimajor axis of giant planets for what we could not see:

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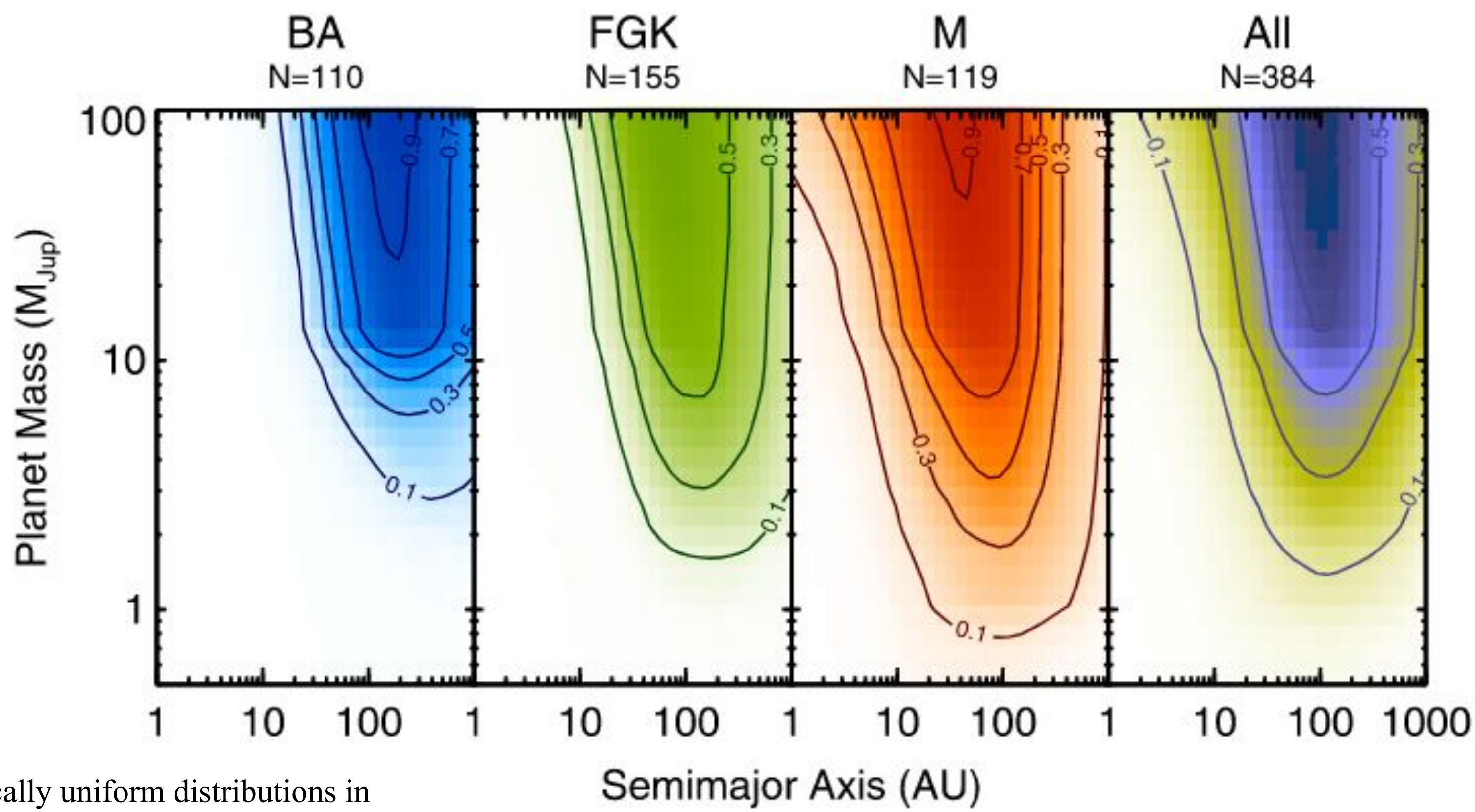

logarithmically uniform distributions in mass and separation

Bowler et al. (2016)

2. First Statistical Studies (<2010)

Various key limitations

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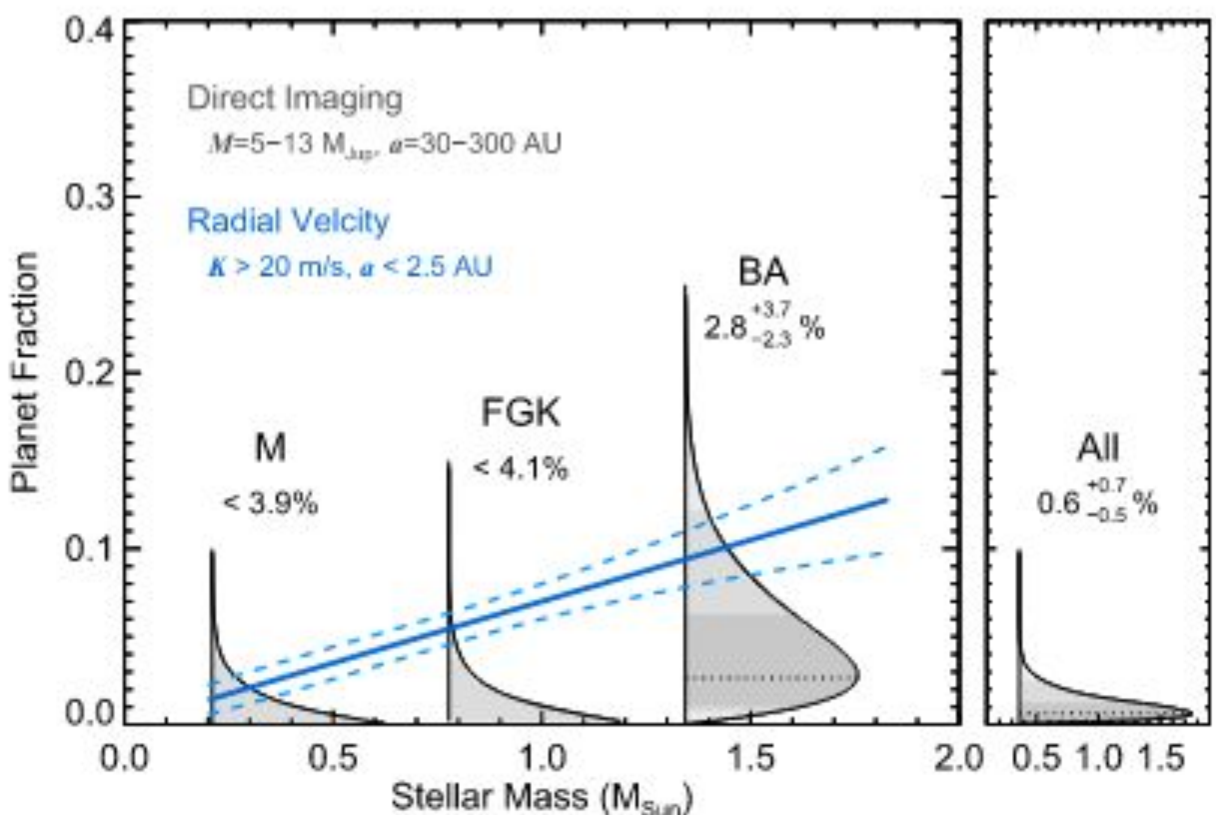

Bowler et al. (2016)

3. Designing the SHINE Survey

By 2014 - 2015, new generation of planet imagers (SPHERE, GPIES, SCExAO…) with large surveys; possibility to address fundamental questions by defining smart samples

Science Objectives:

- New planet discoveries in direct imaging!
- Physics of young Jupiters,
  - especially Young L, T and Y types
  - Atmospheres: Thick clouds, metal-enhancement, non-LTE, effect of low-gravity, photometric variability & Weather studies
  - Mass – Luminosity & evolution to test the Physics of Accretion & Evolution of exoplanets (Hot/Warm/Cold Start models)
- Architecture of planetary systems:
  - Planet – Disk, Planet - Planet interactions,
  - Dynamical stability studies & possible sites for telluric planets…
- Complete census of young Jupiter beyond 5-10 au (around young, nearby A-M stars)
- Occurrence & Formation of giant planets
  - Testing predictions of Planetary Formation theories

Desidera et al. (2021)
Chauvin et al. (2017)

3. Designing the SHINE Survey

Sample selection:

- Young stars near the Sun
  - Planet in emitted light (hotter, brighter when young)
  - Telescope diffraction limited (proximity)

- Building the SHINE catalogue:

  - Statistical sample: 400-600 objects (+400 back-up)
    Selected according to criteria of:
    ✔ Age, distance, stellar mass, brightness (AO performances), declination, binarity exclusion (no SB and close VB)
    ✔ Science priorities: Figure of Merit for planet detection using Power-Law Planet Population :)

  - Special targets: 50 additional targets of special interest outside the boundaries of statistical sample (stars with disks, stars with known substellar companions, etc.)

- SHINE Early statistical analysis (F150): I- Desidera et al. (2021)
  II- Langlois et al. (2021)
  III- Vigan et al. (2021)

3. Designing the SHINE Survey

Sample selection:

- Singles stars,
- Continuum of stellar mass: Explore influence of stellar mass (F, cutoff, CMR); Lower-masses: AO constraint ($R \leq 11.5$); Upper mass limit: 3.0 Msun (Reffert et al. 2013), frequency of RV planets drops.
- Preferences for young, nearby associations members; ages more accurate, optimized for detection; difficult to statistically explore age/dynamical effect;
- Meaningful target list in terms of planet's detection rate and statistics & constraints on planet population. Figure of Merit to set priorities in the database of 800+ stars.

Table 2. Priority distribution of the SHINE sample.

Priority	Early-type	Solar and low-mass
P0	Special targets	
P1	20 MGs + 40 ScoCen	120 MGs + 20 field
P2	20 Field + 40 ScoCen	50 MGs + 90 field
P3	20 Field + 40 ScoCen	140 Field
P4	20 Field + 40 ScoCen	140 Field
P5	Bad weather backup or filler	

3. Designing the SHINE Survey

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- Preferences for young, nearby associations members; ages more accurate, optimized for detection; difficult to statistically explore age/dynamical effect;
- Meaningful target list in terms of planet's detection rate and statistics & constraints on planet population. **Figure of Merit** to set priorities in the database of 800+ stars.
- Extension:
  - Geneva 2015: Extension to new M dwarfs (SAXO perfs + too faint for GPI)
  - Padova 2016: Extension to add. Sco Cen targets for intermediate stars
  - Edinburgh 2017: Top priority given to Sco Cen (given discovery rate)

Desidera et al. (2021)

3. Designing the SHINE Survey

Targets boosted as P0 “Special” Targets:

Table 3. Stars in the SHINE statistical sample observed as special targets (highest priority).

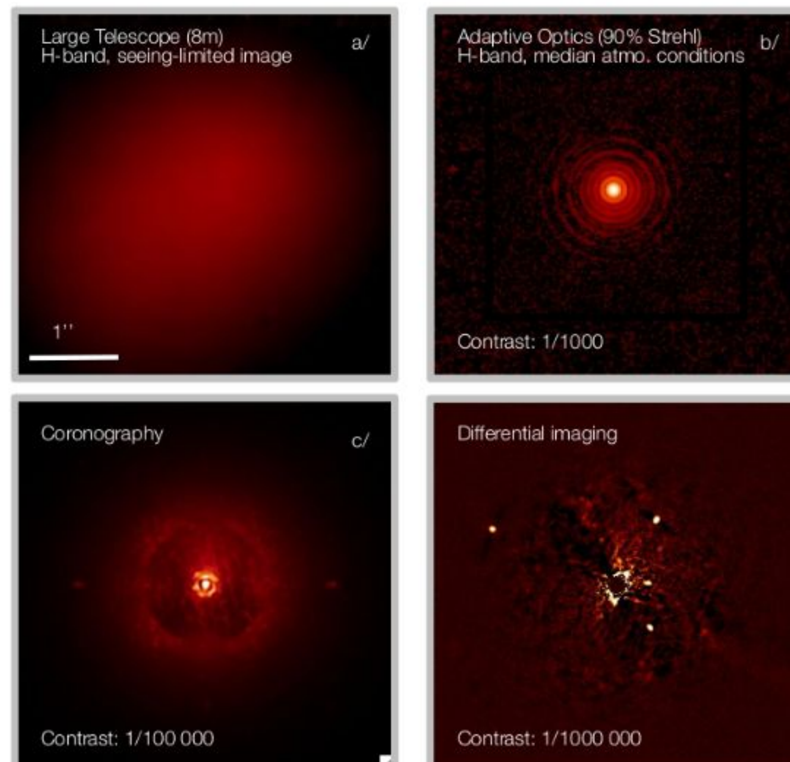
Target	Priority	Remarks	Discovery paper	SPHERE paper
β Pic	P1	Known planet and disk	Lagrange et al. (2009)	Lagrange et al. (2019)
HR 8799	P1	Known planet	Marois et al. (2008)	Zurlo et al. (2016)
HD 95086	P1	Known planet	Rameau et al. (2013b)	Chauvin et al. (2018)
Fomalhaut	P2	Known planet and disk	Kalas et al. (2008)	–
FomalhautB	P3	Companion to P0 star	–	–
PZ Tel	P1	Known brown dwarf	Biller et al. (2010)	Maire et al. (2016)
HIP 107412	P4	Known brown dwarf	Milli et al. (2017)	Delorme et al. (2017); Grandjean et al. (2019)
51 Eri	P1	Known planet	Macintosh et al. (2015)	Samland et al. (2017); Maire et al. (2019)
AB Pic	P1	Known brown dwarf	Chauvin et al. (2005b)	–
TYC 8047-0232-1	P1	Known brown dwarf	Chauvin et al. (2005a)	–
HIP 78530	P1	Known brown dwarf	Lafrenière et al. (2011)	–
HD 61005	P1	Known disk	Hines et al. (2007)	Olofsson et al. (2016)
HR 4796	P1	Known disk	Schneider et al. (1999)	Milli et al. (2017, 2019)
AU Mic	P1	Known disk	Liu (2004)	Boccaletti et al. (2015, 2018)
HD 30477	P1	Known disk	Soummer et al. (2014)	
TWA 7	P1	Known disk	Choquet et al. (2016)	Olofsson et al. (2018)
HD 141943	P2	Known disk	Soummer et al. (2014)	Boccaletti et al. (2019)
ζ Lep	P2	Known disk	Moerchen et al. (2010)	
ρ Vir	P1	Known disk	Booth et al. (2013)	–
HIP 71724	P3	Known low-mass comp.	Hinkley et al. (2015)	–
HIP 73990	P3	Known low-mass comp.	Hinkley et al. (2015)	–
HD 115600	P3	Known disk	Currie et al. (2015)	–
HD 377	P2	Known disk	Choquet et al. (2016)	–

Notes. The original priority in the selection of the statistical sample, the motivation for priority upgrade, and the references to discovery papers and individual SPHERE papers are listed. SAM stands for sparse aperture masking (e.g., Tuthill et al. 2006).

3. Designing the SHINE Survey

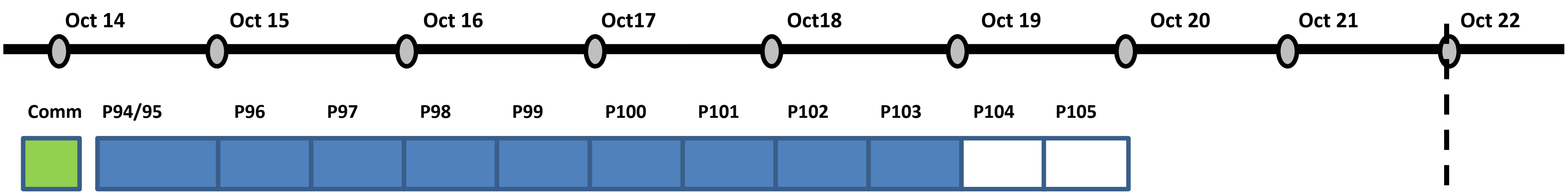
Observing Strategy

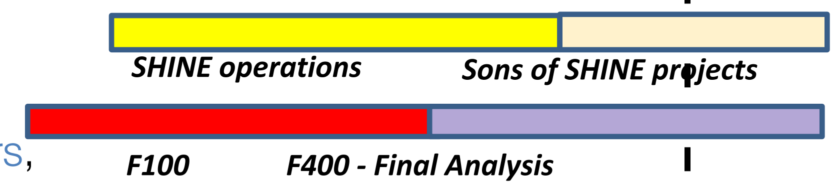
- SPHERE nIR instruments
  - Coronography: Apodized Lyot Coronograph
  - IRDIS in H23 (K1K2, ScoCen) AND IFS in Y-J (YJH, ScoCen) simultaneously
  - Angular and spectral differential Imaging; Sequence of 2hrs/visit



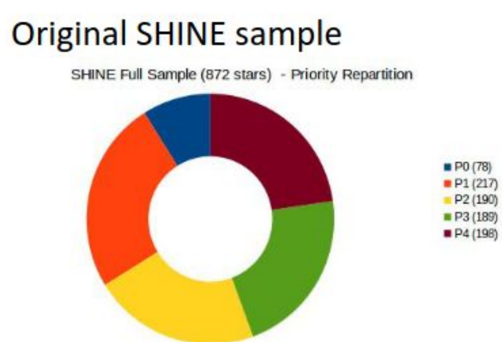
3. Designing the SHINE Survey

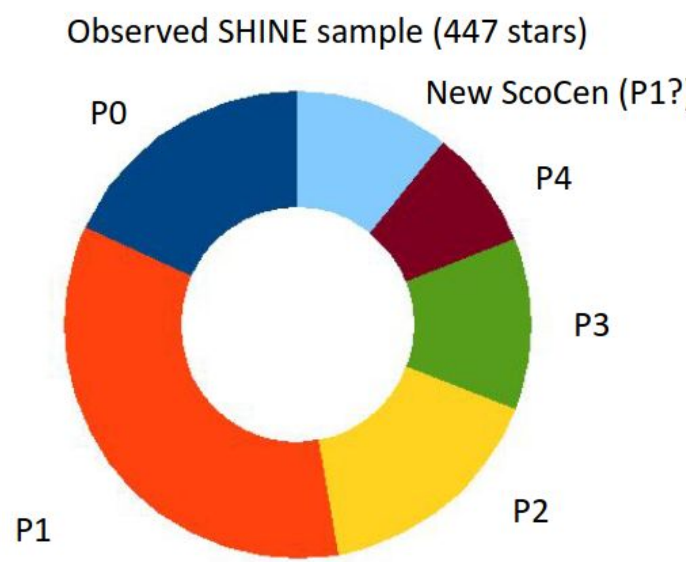
Observing Timeline





- SHINE Visits = 831, SHINE validated Visits = 662
- SHINE Targets with Validated Observations 447 stars, including 376 (F400)
- Repartition per Science Priority:

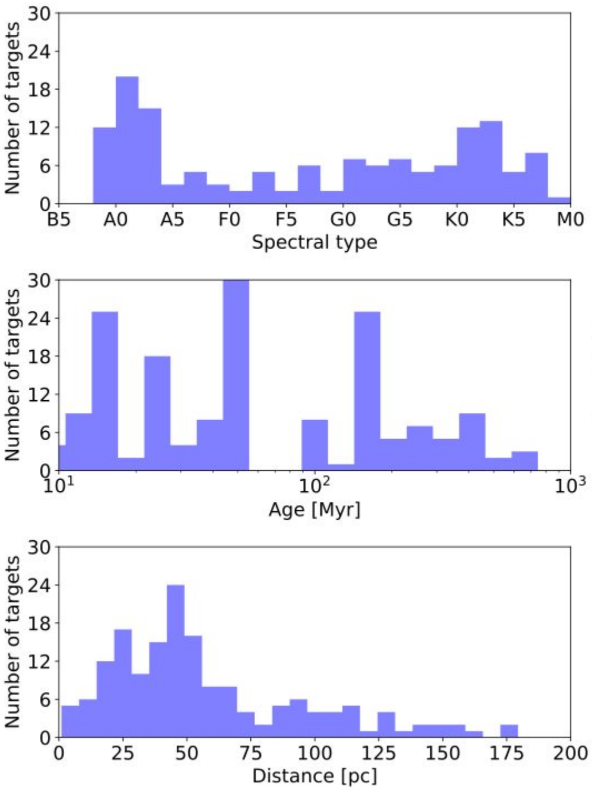


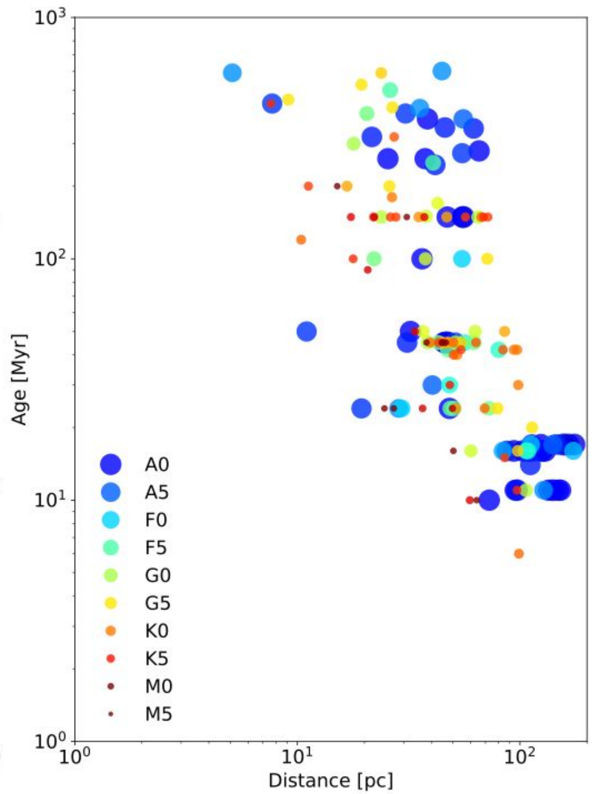


Raffaele's IFS numbers

4. SHINE-F150 Demographics Study

F150 Sample





. 150 targets

. 4+1 priority bins:
- P1 to P4,
- P0 for special targets

. observed by order of priority
+ external parameters (date, obs. conditions, etc)

· intermediate sample representative of the full SHINE sample
· no significant bias in spectral type/distance/age
· *but* bias towards P0 targets because of known companions

Desidera et al. (2021)

4. SHINE-F150 Demographics Study

Priorities, Detections & Statistical Weights

Assumption #1

Table 1. Substellar companions detected around targets within the current sample.

Companion	SpT	$M_\star$ $[M_\odot]$	Semimajor axis [au]	Mass $[M_{\rm Jup}]$	q $M_p/M_\star$ [%]	Original priority	Updated priority	Statistical weight	References
				New SHINE detections					
HIP 64892 B	B9	2.09	147–171	29–37	1.3–1.7%	P1		1.00	1
HIP 65426 b	A2	1.96	80–210	7–9	0.3–0.4%	P1		1.00	2, 3
				Previously known detections – no priority update					
η Tel B	A0	2.00	125–432	20–50	1.0–2.4%	P1		1.00	4, 5
CD -35 2722 B	M1	0.56	74–216	23–39	3.9–6.6%	P1		1.00	6, 5
				Previously known detections – updated priority					
HIP 78530 B [(a)]	B9	1.99	~620	19–26	0.9–1.2%	P1	P0	0.60	7
β Pic b	A3	1.61	8.5–9.2	9–16	0.5–0.9%	P1	P0	0.60	8, 9
HR 8799 b	A5	1.42	62–72	5.3–6.3	0.3–0.4%	P1	P0	0.60	10
HR 8799 c	A5	1.42	39–45	6.5–7.8	0.4–0.5%	P1	P0	0.60	10
HR 8799 d	A5	1.42	24–27	6.5–7.8	0.4–0.5%	P1	P0	0.60	10
HR 8799 e	A5	1.42	14–17	6.5–7.8	0.4–0.5%	P1	P0	0.60	10
HD 95086 b	A8	1.55	28–64	2–9	0.1–0.6%	P1	P0	0.60	11, 12
51 Eri b	F0	1.45	10–16	6–14	0.4–0.9%	P1	P0	0.60	13, 14
HIP 107412 B	F5	1.32	6.2–7.1	15–30	1.1–2.2%	P4	P0	0.01	15, 16
PZ Tel B	G9	1.07	19–30	38–54	3.4–4.8%	P1	P0	0.60	17, 18
AB Pic B	K1	0.97	~250	13–30	1.3–3.0%	P1	P0	0.60	19, 20
GSC 8047-0232 B	K2	0.89	190–880	15–35	1.6–3.8%	P2	P0	0.35	21, 22

Priority P1: 60% probability of observation (P_{obs})
Priority P2: 35% probability of observation
Priority P4: 1% probability of observation

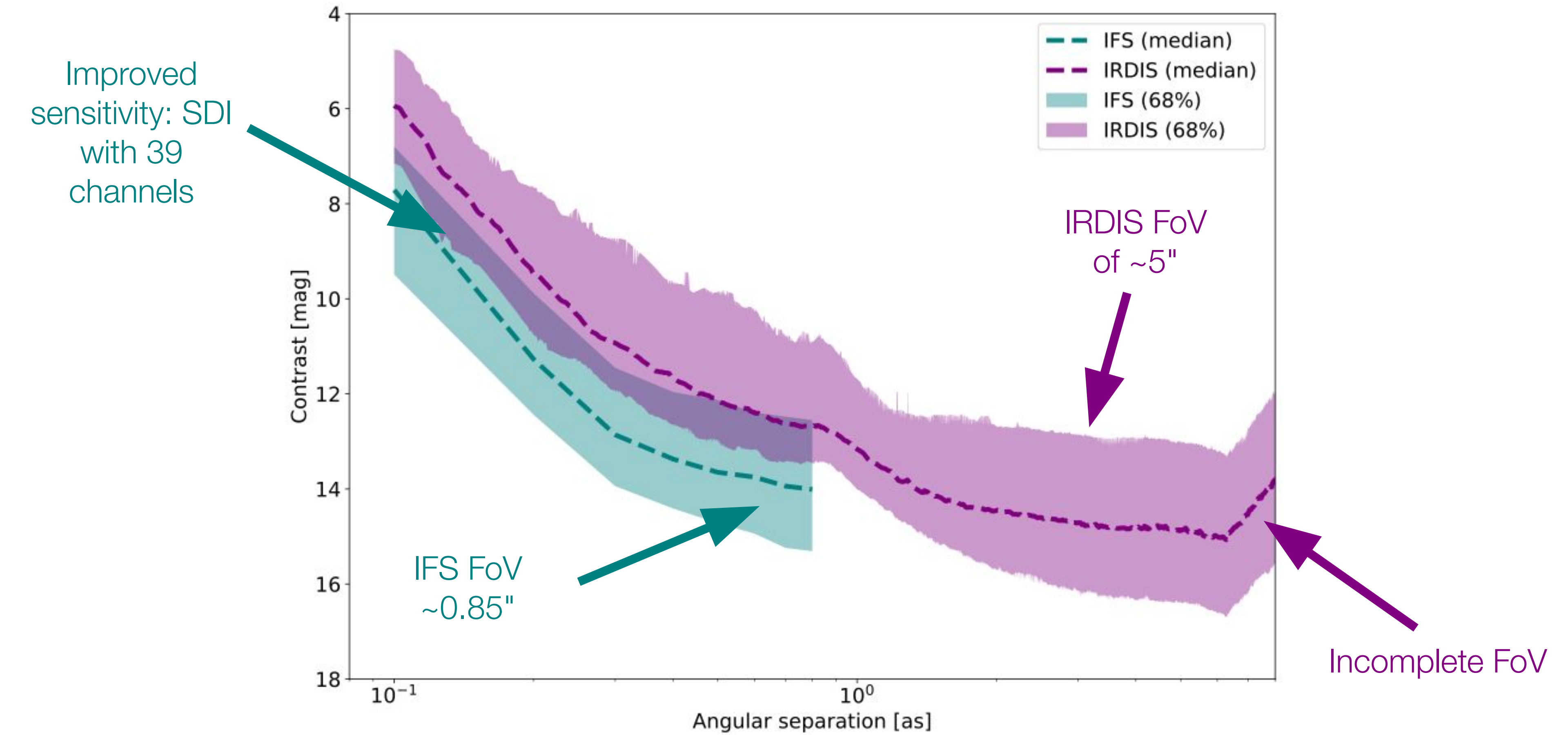
Change to P0 creates a real bias; count "effective detections" for the analysis:

$$N_{det}^{eff} = \sum_{i=1}^{N_\star} P_{obs,i} N_{det,i}$$

4. SHINE-F150 Demographics Study

Detection performances

Assumption #2: white/gaussian noise and detection probabilities



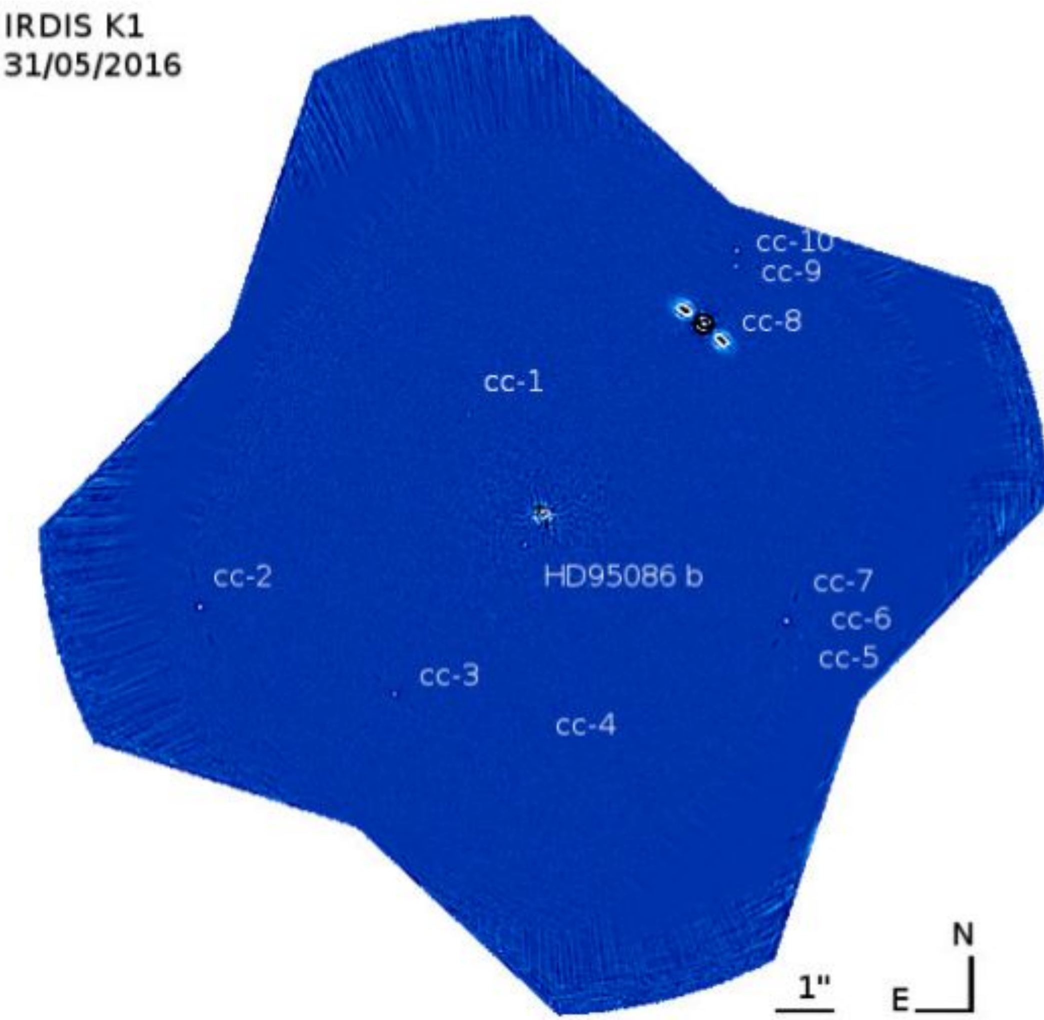
- Most observations in IRDIFS mode + some in IRDIFS-EXT (e.g. ScoCen targets)
- Speckle subtraction with SpeCal at SPHERE data center (Galicher et al. 2018)
- T-LOCI analysis for IRDIS (H2 filter) / ASDI PCA for IFS (all channels)

Langlois et al. (2021)

4. SHINE-F150 Demographics Study

Substellar Candidates

Langlois et al. (2021)



Diagnostics:

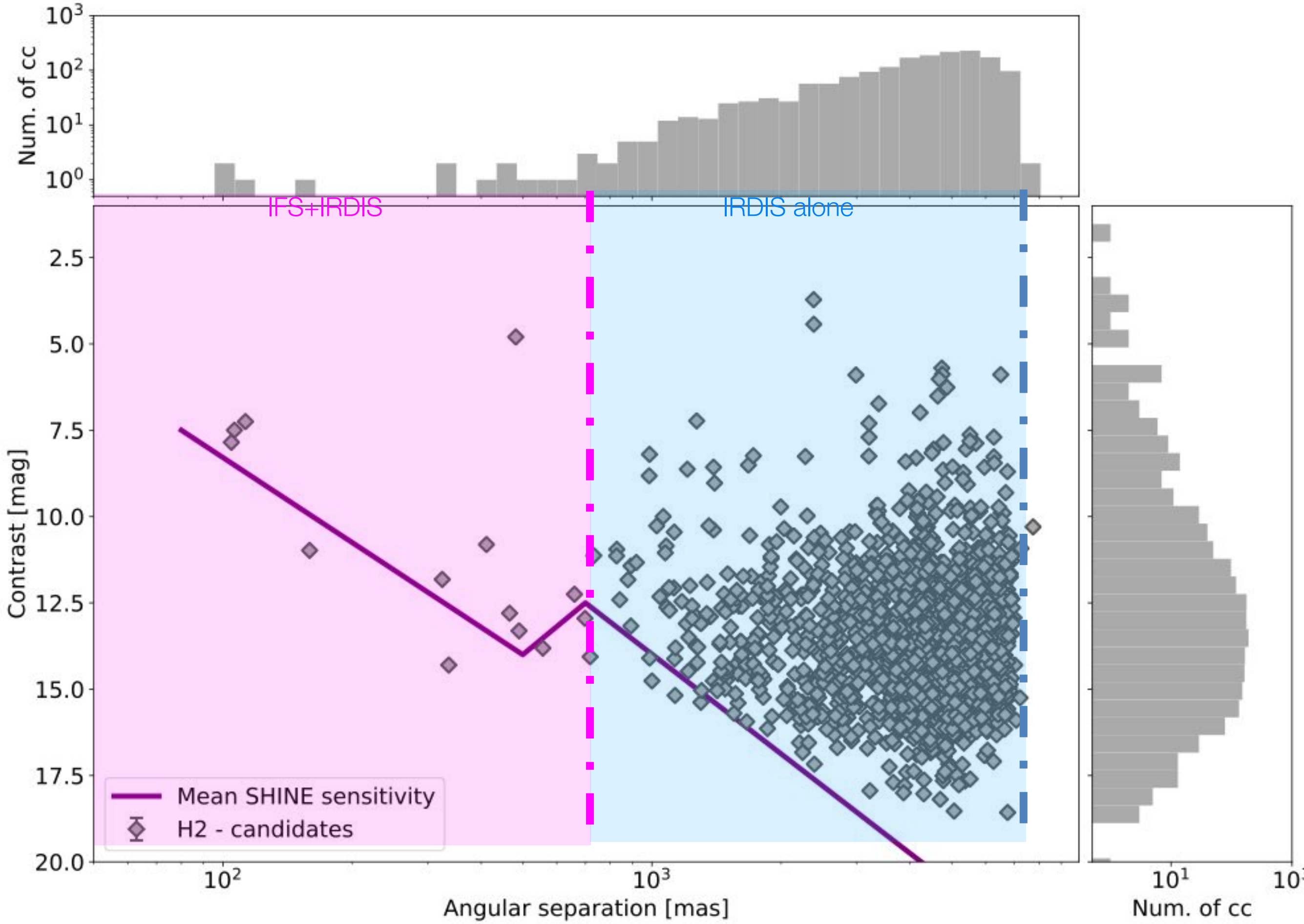
. IFS: on a case-by-case basis

. IRDIS:

- *Level 0: merit function based on expected properties (mass, sma), contamination probability and stellar proper motion (not used, or simple a_{cutoff})*
- Level 1: CMD position
- Level 2: PMD Proper motion

4. SHINE-F150 Demographics Study

Substellar Candidates

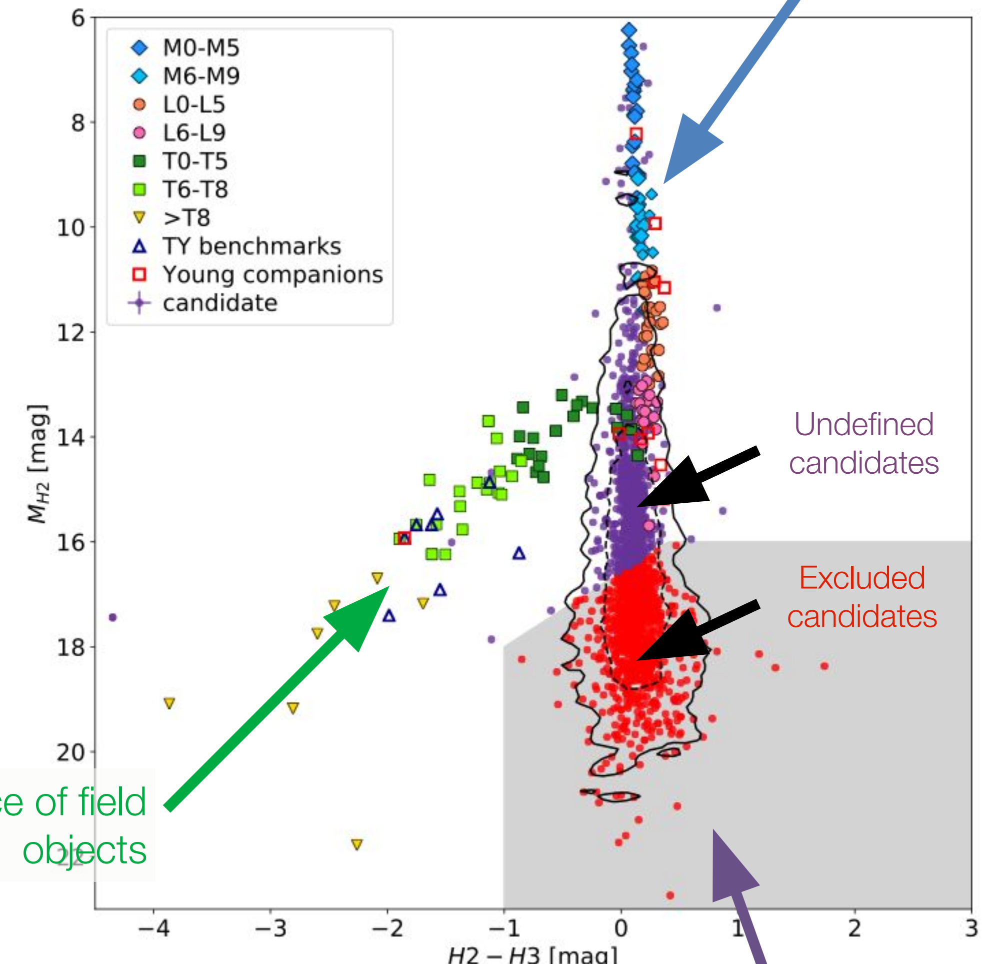


- 1491 sub-stellar candidates detected around 89 targets: 53% contamination
- >95% outside of IFS FoV

4. SHINE-F150 Demographics Study

CMD

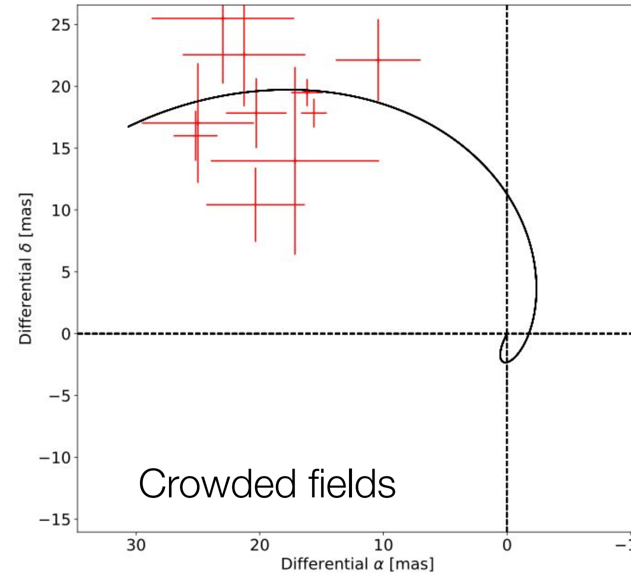
- IRDIS filters: color-magnitude diagrams
  - H2 vs (H2-H3)
  - K1 vs (K1-K2)
- comparison to MLTY sequence + known young companions
  - comparison for each candidate
- empirical exclusion region:
  - rejection of the most unlikely candidates
- most efficient in H23 filter

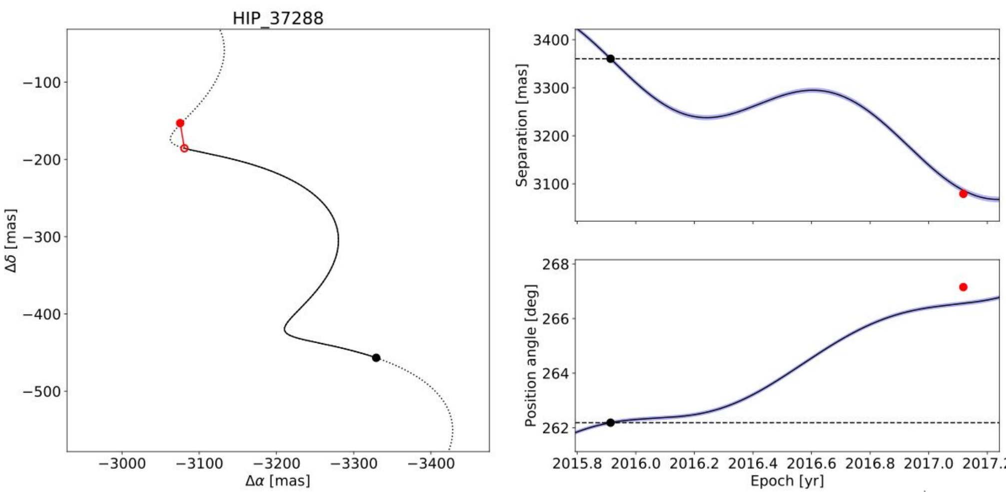


4. SHINE-F150 Demographics Study

PMD

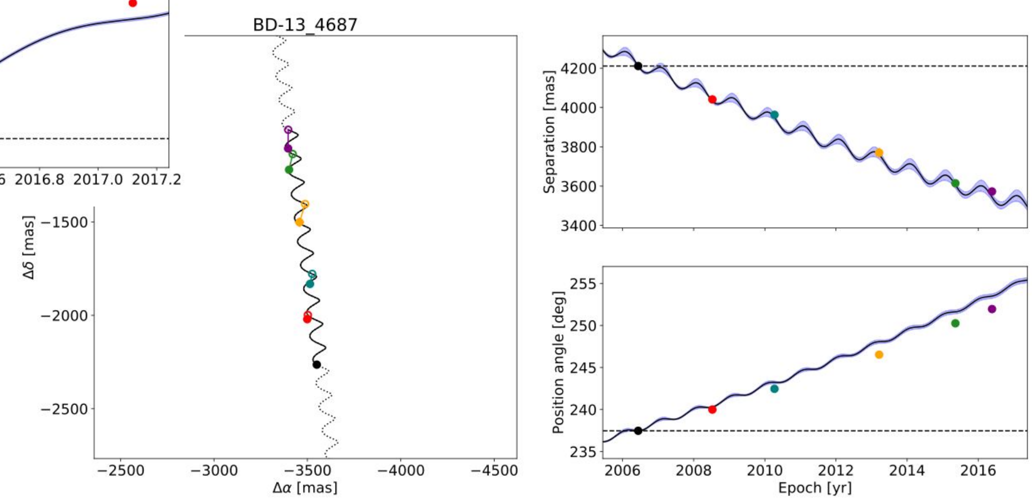
- Status of most candidates unknown a priori
- Primary tool: astrometric confirmation
  - SHINE second epochs
  - public databases ➞ *DIVA* & *TDB* @ LAM
  - archival data analysis





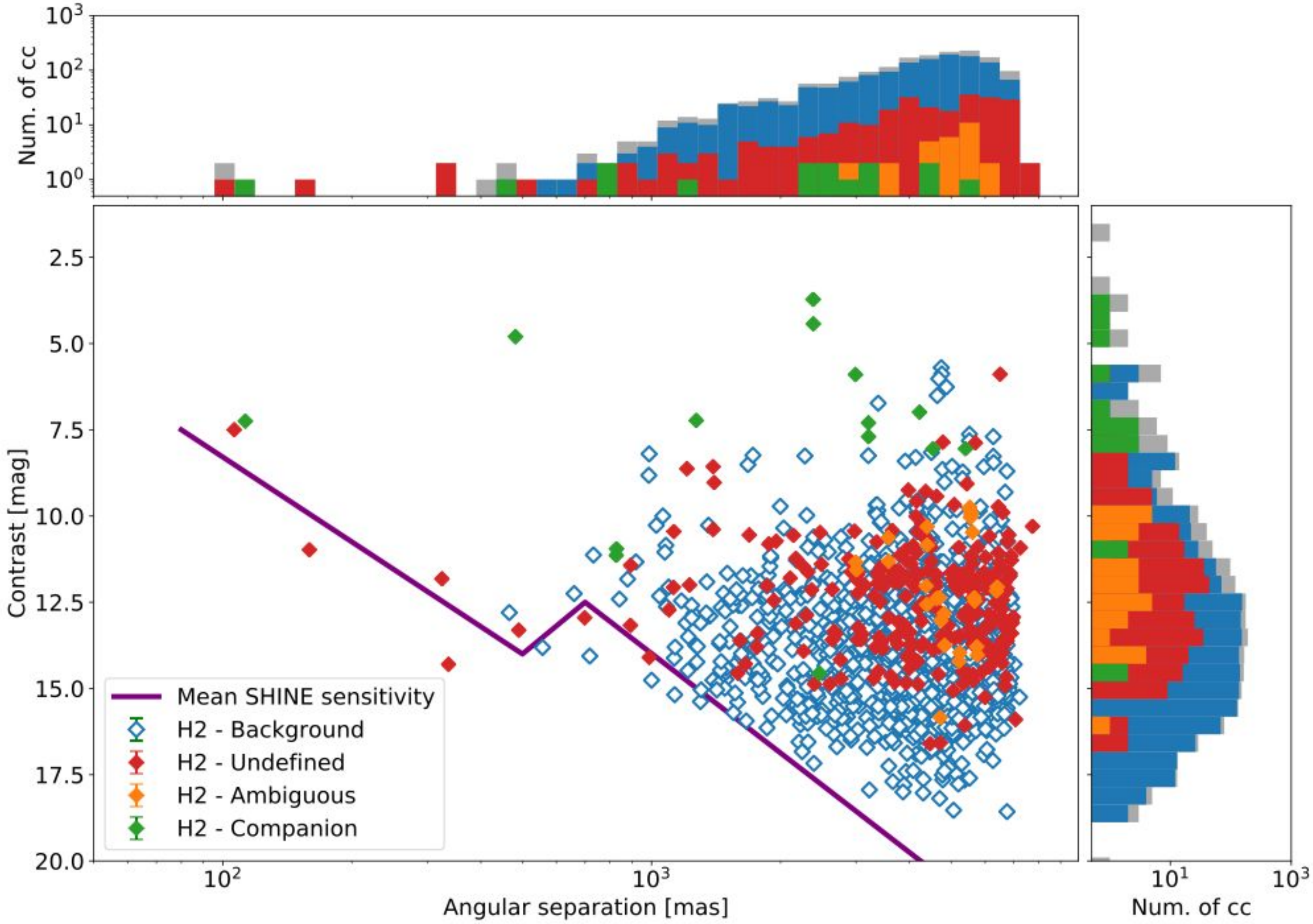
SHINE data

SHINE + archive data



4. SHINE-F150 Demographics Study

Candidate identification

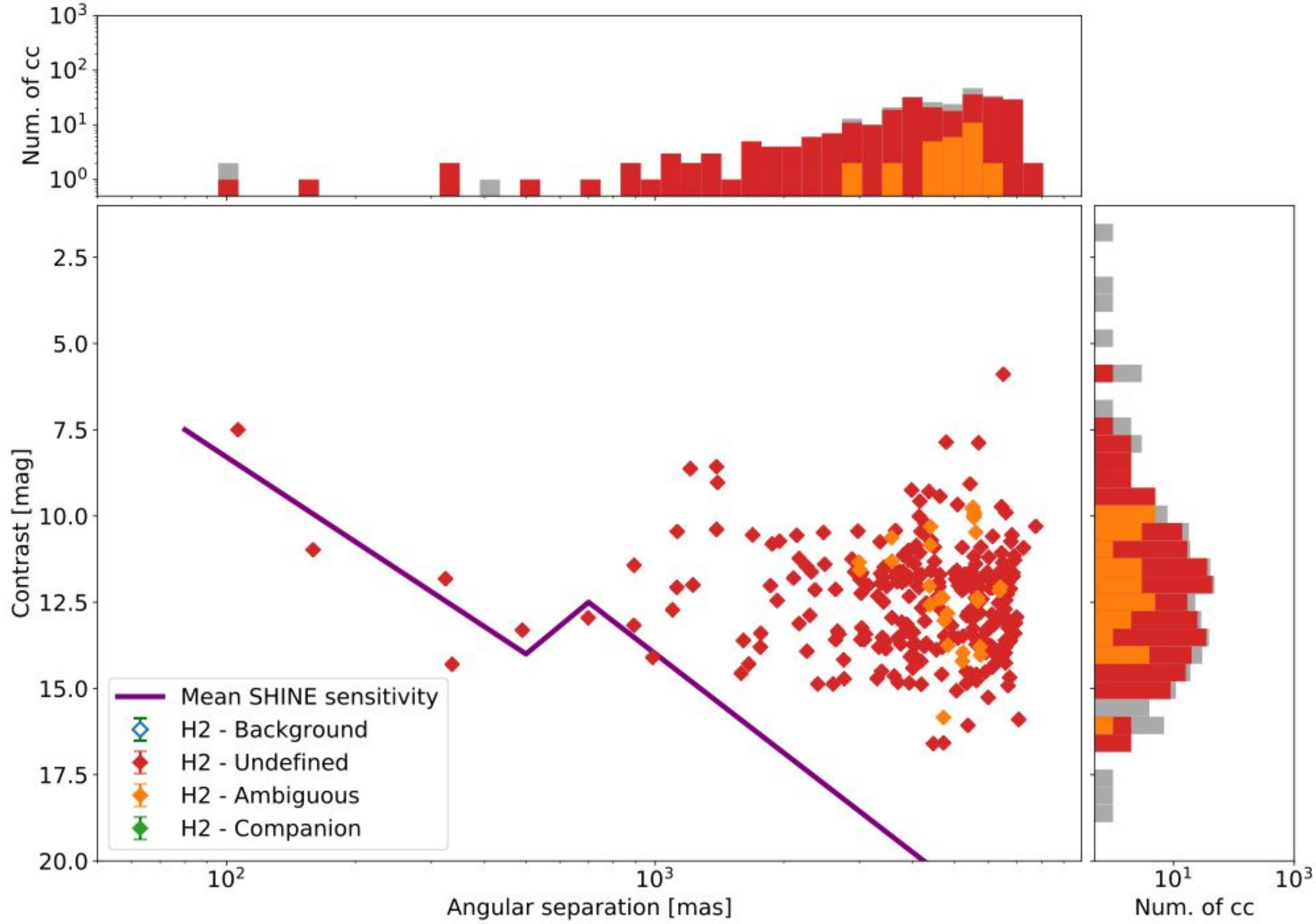


Classification using astrometry and color-magnitude diagram rejection:

→ 355 undefined candidates

4. SHINE-F150 Demographics Study

Candidate identification



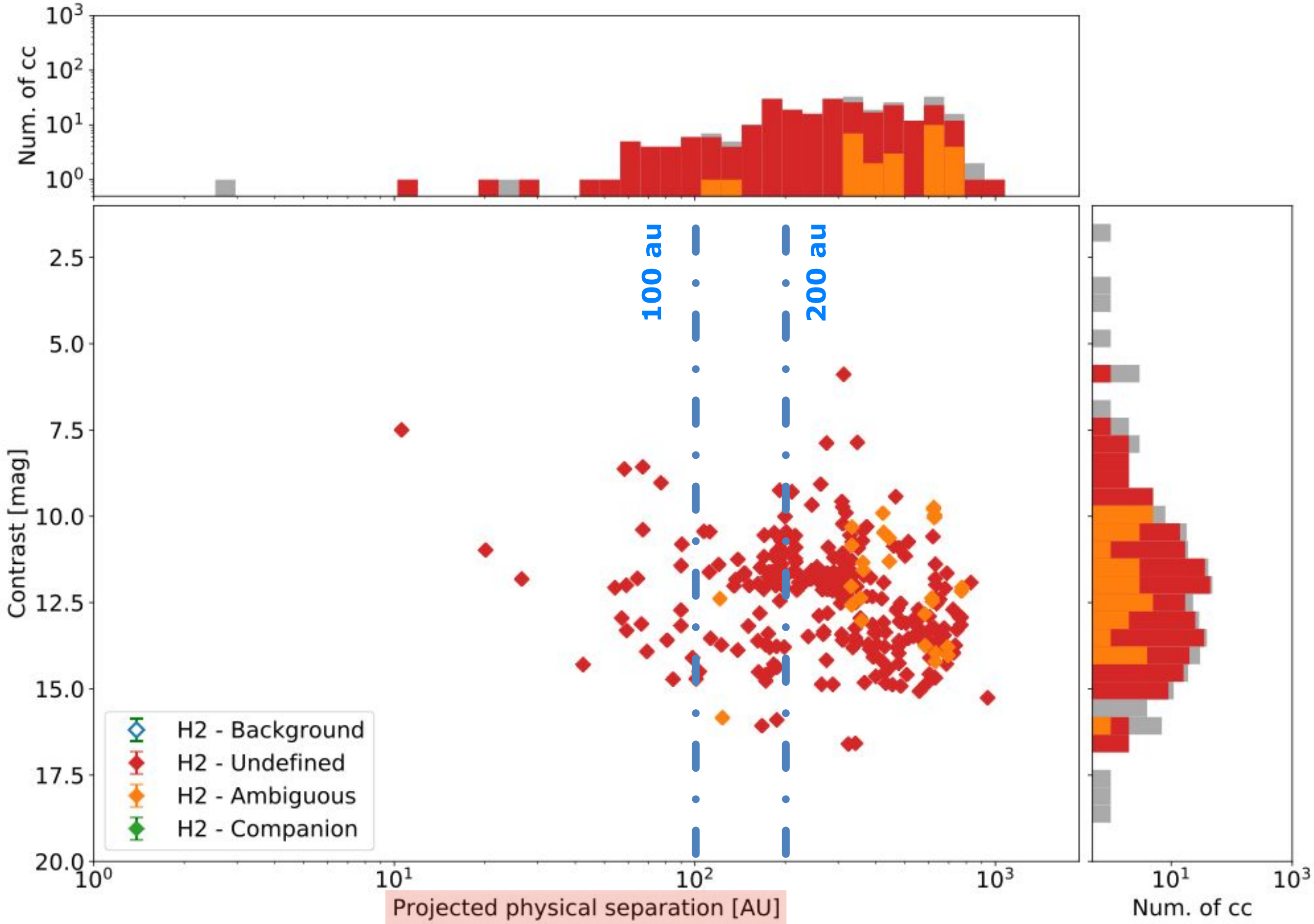
Classification using astrometry and color-magnitude diagram rejection:

→ 355 undefined candidates

4. SHINE-F150 Demographics Study

Candidate identification

Assumption #3: all U/A candidates are BKG



Undefined candidates: ~30 within 100 au, ~100 within 200 au

→ need to apply cutoff in the statistical analysis

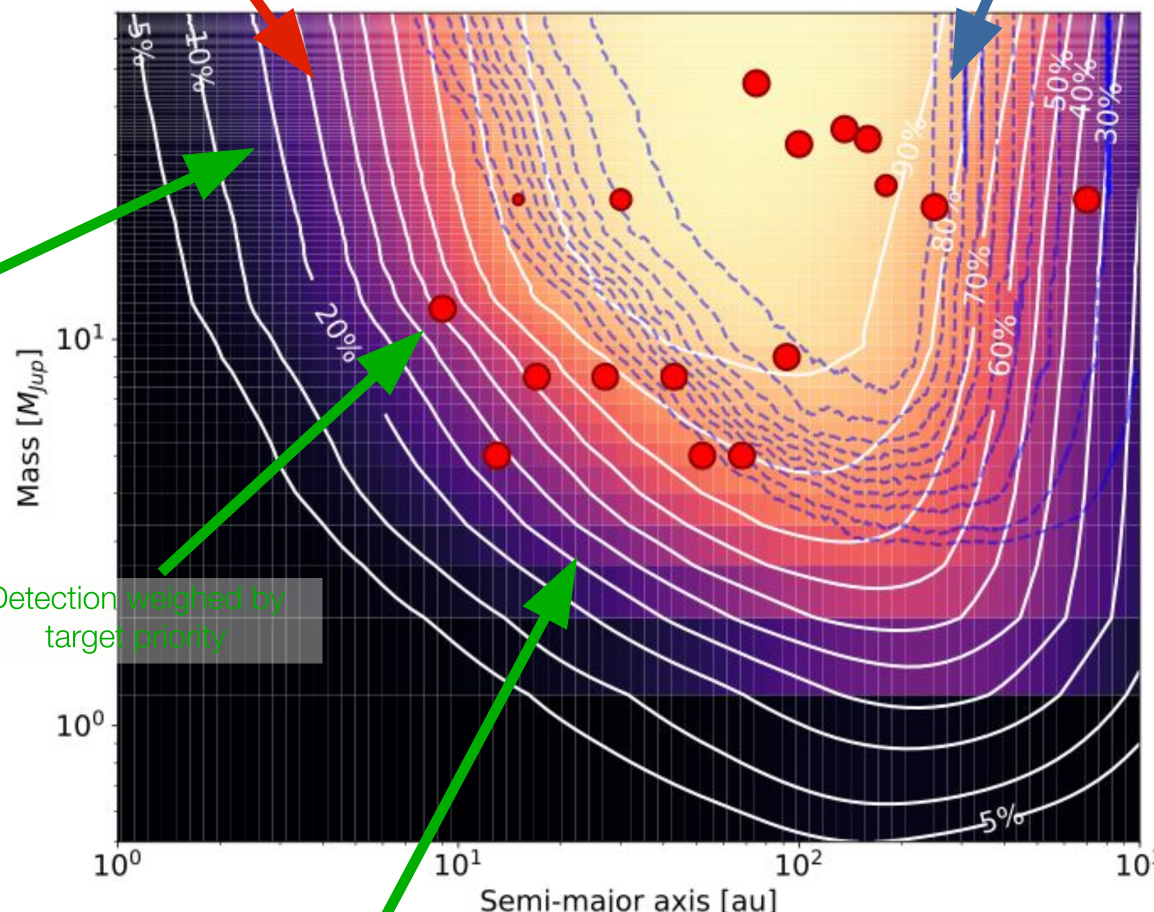
4. SHINE-F150 Demographics Study

Completeness

Mass conversion with Baraffe et al. models (Baraffe+ 2003, 2015)
+ Monte-Carlo analysis with MESS tool (Bonavita, Chauvin 2012)

SHINE detection probabilities

NaCo-LP detection probabilities



Some sensitivity down to 2-3 au

Detection weighed by target priority

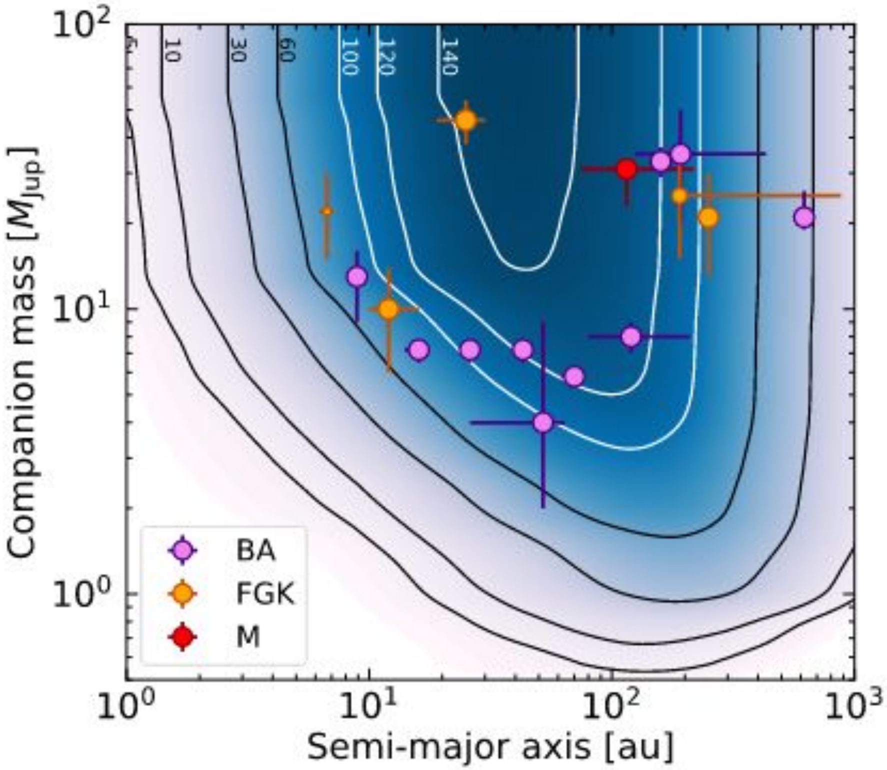
Major sensitivity gain in 10-50 au
x10 in mass at some semi-major axes

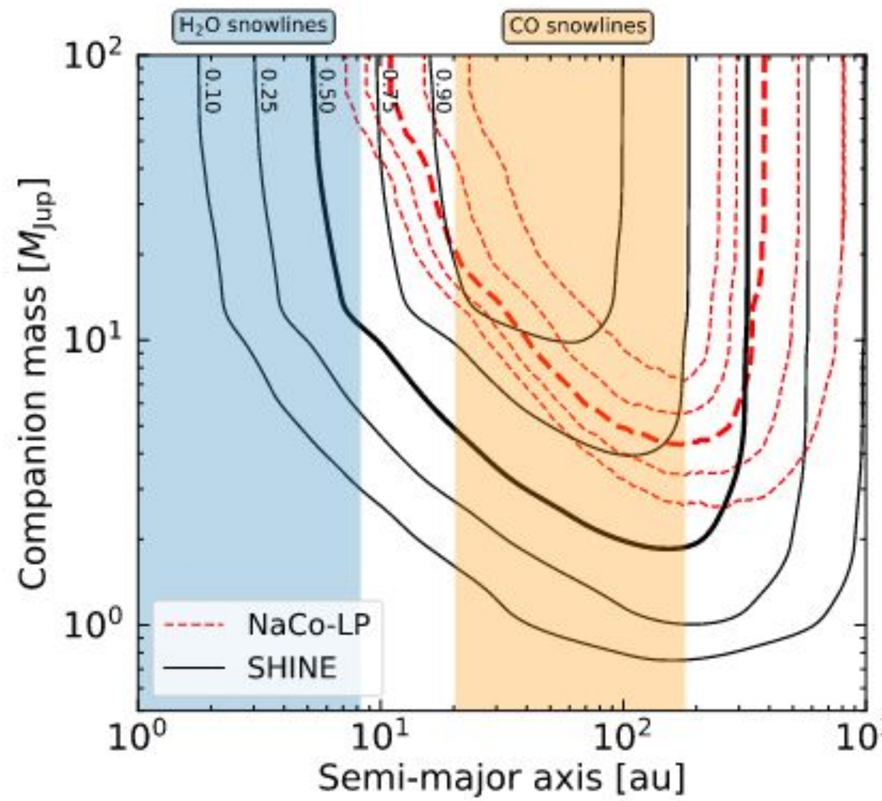
Hypothesis:
- all spectral types
- nominal age for stars
- undefined candidates ignored → background
- companions distribution:
  - flat in mass
  - flat in semi-major axis

4. SHINE-F150 Demographics Study

Completeness

- Companions per spectral types
- Detection limits and snowlines

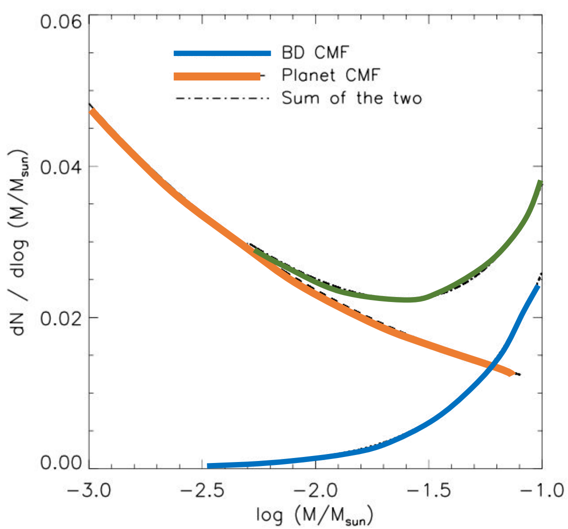




4. SHINE-F150 Demographics Study

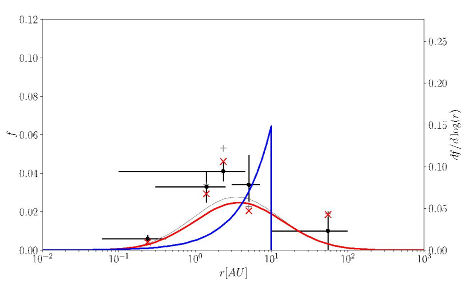
Parametric models, still alive!

Companion Mass Ratio Distribution (CMRD)



$q = M_{COMP}/M_*$ **$dN/dq \sim q^{-1.3\ -1.9}$** **$dN/dq \sim q^{0.25}$**

Orbital Frequency: Planetary Companions (1-10 M_{JUP})



log-normal distribution!
A Stars: 6 AU peak.
FGK Stars: 4 AU peak.
M Dwarfs: 3 AU peak.

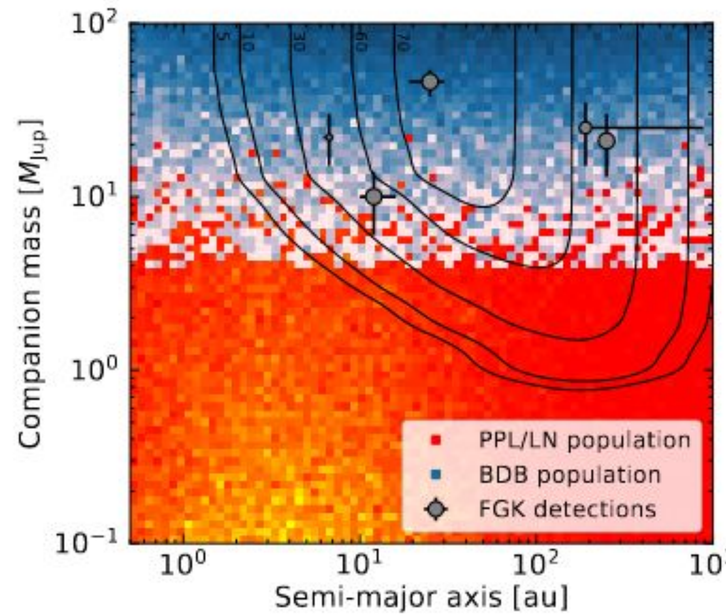
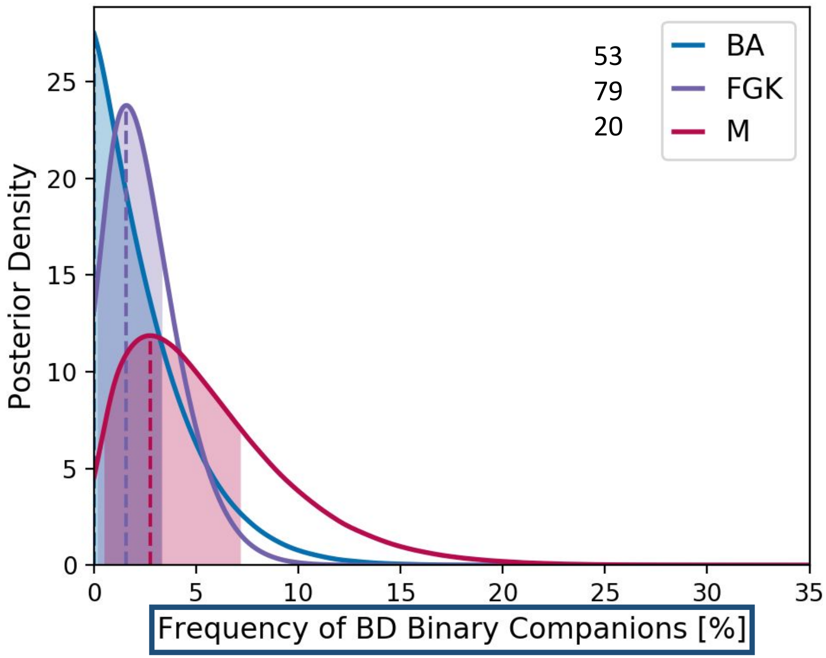


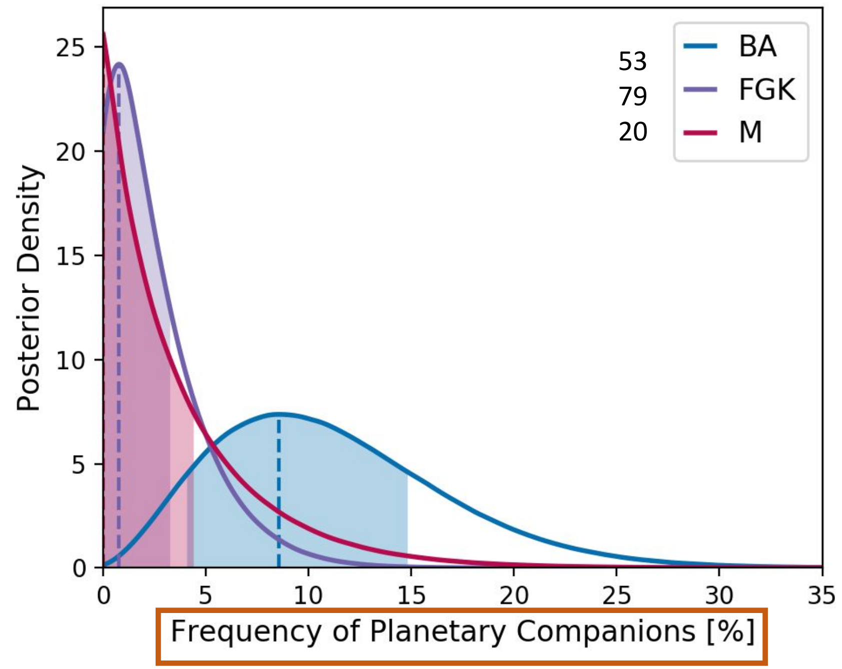
Fig. 3. Comparison of the depth of search of the SHINE survey for the 77 FGK stars in the sample with a population of 20 000 draws from our parametric model presented in Sect. 3.1. The contour lines give the numbers of stars around which the survey is sensitive to substellar companions as a function of mass and semimajor axis. The PPL/LN part of the model is represented with shades of red (low density of companions) to yellow (high density of companions), and the BDB part of the model is represented with shades of white (low density of companions) to blue (high density of companions). Only the detections around FGK stars are plotted.

4. SHINE-F150 Demographics Study

Parametric models, still alive!

- Occurrence rate versus stellar mass
- Increase of the occurrence of giant planets with the mass of the stellar host
- Increase of the occurrence of brown binary companion for low-mass stars





4. SHINE-F150 Demographics Study

Population synthesis models (CA, GI)

Core Accretion (Mordasini et al.)

- population NG76 NGPPS
- Self-consistent model: 1D gas disk, the dynamical state of the solids, the accretion by the protoplanets, gas-driven migration of the protoplanets, the interiors of the planets, and their dynamical interactions.
- No interactions between planets

Gravitational Instability (Forgan et al.)

- 1D disk models that smoothly proceed from an epoch in which the GI dominates their evolution.
- The fragments then followed a tidal downsizing process where they contracted and cooled, and evolved through disk migration
- and n-body interactions.

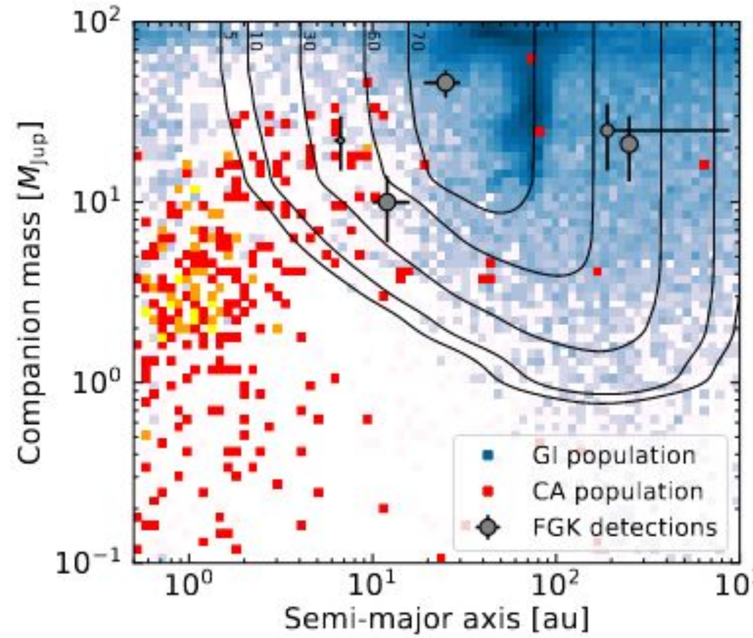


Fig. 4. Comparison of the depth of search of the SHINE survey for the 77 FGK stars in the sample with the population synthesis models based on the CA and GI formation scenarios presented in Sects. 3.2.1 and 3.2.2, respectively. The contour lines give the numbers of stars around which the survey is sensitive to substellar companions as a function of mass and semimajor axis. The CA companions are represented with shades of red (low density of companions) to yellow (high density of companions), and the GI companions are represented with shades of white (low density of companions) to blue (high density of companions). The apparent lower density of CA objects arises because the vast majority of the CA population is located outside the range of mass and semimajor axis considered in this plot. Only the detections around FGK stars are plotted.

4. SHINE-F150 Demographics Study

Population synthesis models (CA, GI)

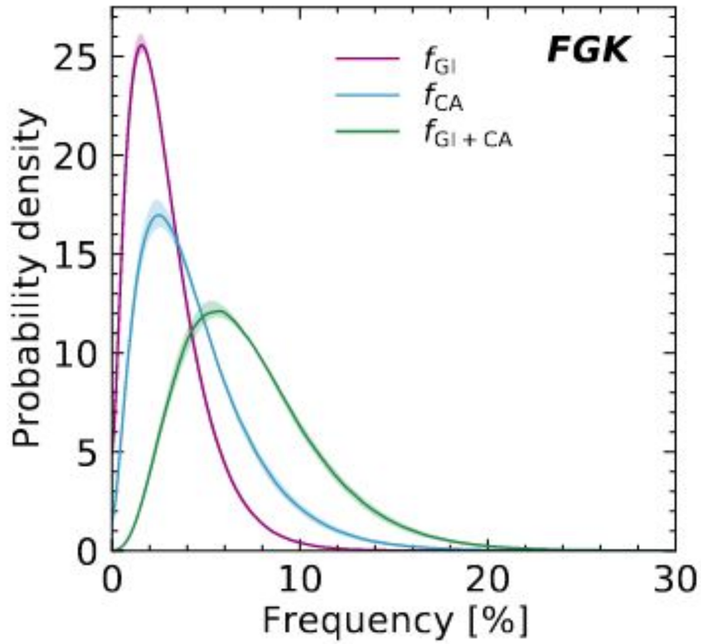


Fig. 9. Probability density functions of the frequencies of substellar companions around FGK stars based on the population model, computed for companions with masses in the range $M_p = 1–75\ M_{Jup}$ and semimajor axes in the range $a = 5–300$ au, and using the BEX-COND-hot evolutionary tracks for the mass conversion of the detection limits. Each plot shows the PDFs for the relative frequencies of the two components of the model (f_{GI} and f_{CA}), and for the total frequency for the full model (f_{GI+CA}). The plain lines show the PDFs for the nominal stellar ages, and the shaded envelopes show the variation of these PDFs for the maximum and minimum stellar ages. The median values and 68% confidence intervals are provided in Table 2.

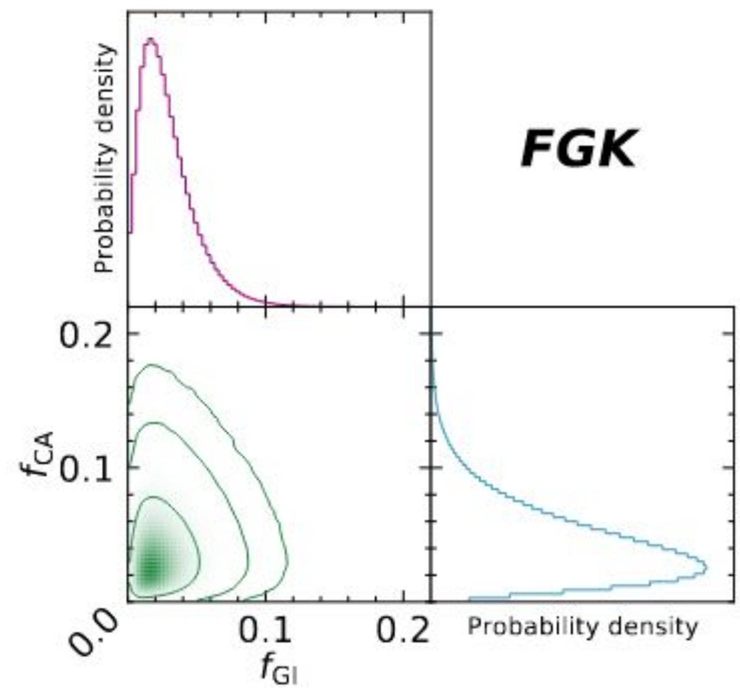


Fig. 10. Correlation plots and marginalized PDFs for f_{GI} and f_{CA} in the population model around FGK stars, computed for companions with masses in the range $M_p = 1–75\ M_{Jup}$ and semimajor axes in the range $a = 5–300$ au, and using the BEX-COND-hot evolutionary tracks at the optimal stellar ages. Contour lines in the correlation plots correspond to regions containing 68, 95, and 99% of the posterior, respectively.

4. SHINE-F150 Demographics Study

Key conclusions

F150-SHINE survey
(200 GTO nights SPHERE)
150/500 FKG (50-500 Myr) stars

Occurrence of planetary systems with at least 1 giant planet (10 - 1000 ua, M > 1 M_{Jup}):

- *freq.*(FGK) = $5.7^{+3.8}_{-2.8}$ %

- Overlap of 2 populations:
  Brown dwarfs (stellar formation)
  & planets,

- Increase of the *freq.* of giant planets with the mass of the stellar host

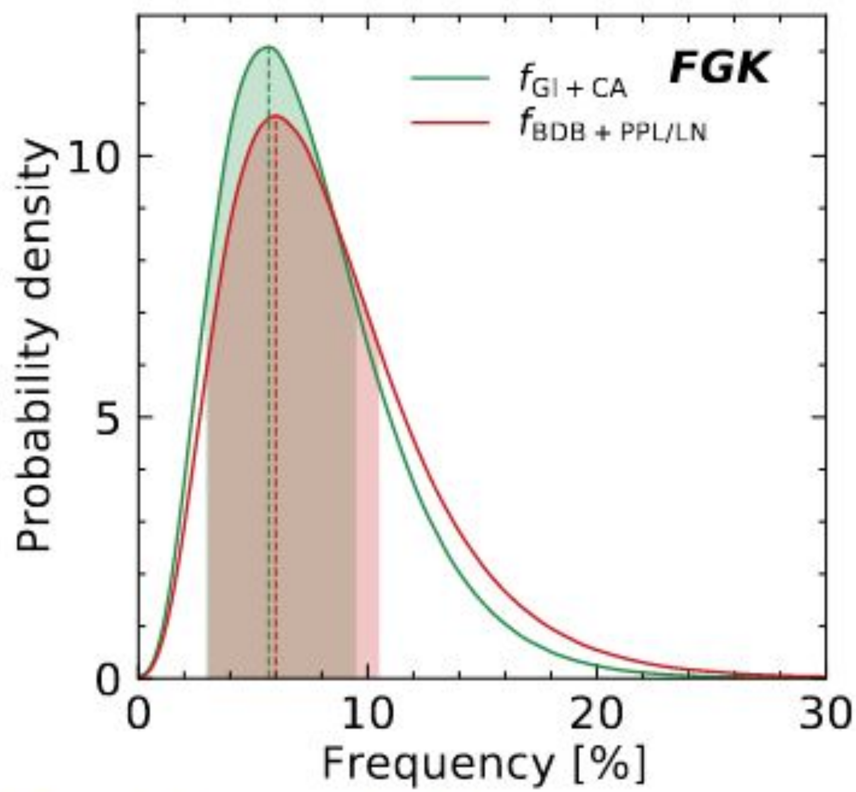


Fig. 11. Comparison of the PDF of the frequency of systems with at least one companion for the full parametric and population models, $f_{BDB+PPL/LN}$ and f_{GI+CA}, respectively.

4. SHINE-F150 Demographics Study

Key conclusions & other works

Table 3. Comparison of SHINE results based on our parametric model with previously published work.

Study	Mass [M_{Jup}]	S.m.a.[b] [au]	Distribution	SpT	Published study Median [%]	Published study 68% CI[c] [%]	SHINE Median [%]	SHINE 68% CI [%]	Compatible[a]
Vigan et al. (2012)	3–14	5–320	Uniform	AF[d]	8.7	5.9–18.8	6.1	3.2–11.3	✓
	15–75	5–320	Uniform	AF[d]	2.8	2.0–8.9	9.0	5.6–14.0	✓
Galicher et al. (2016)	4–14	25–940	Uniform	BA	1.9	0.5–10.1	2.7	1.7–4.4	✓
	4–14	25–940	Power law	BA	2.1	0.5–11.1	2.7	1.7–4.4	✓
	4–14	25–856	Uniform	FGK	1.2	0.6–6.6	0.5	0.3–0.9	✓
	4–14	25–856	Power law	FGK	1.1	0.3–6.1	0.5	0.3–0.9	✓
	1–13	10–200	Uniform	M		<9.2	1.6	0.5–4.5	✓
	1–13	10–200	Power law	M		<11.9	1.6	0.5–4.5	✓
Lannier et al. (2016)	2–14	8–400	Uniform	M	2.3	1.6–8.1	2.0	0.1-4.5	✓
Bowler (2016)	5–13	10–100	Uniform	BA	7.7	1.7–16.7	2.2	1.2–4.1	✗
	5–13	10–100	Uniform	FGK		<6.8	0.3	0.1–0.8	✓
	5–13	10–100	Uniform	M		<4.2	0.8	0.3–1.7	✓
Vigan et al. (2017)	0.5–75	20–300	Uniform	FGK	2.1	1.5–4.5	3.5	1.9–6.2	✓
Nielsen et al. (2019)	2–13	3–100	Uniform	BA	24	14–37	8.6	4.1–15.9	✗
	2–13	3–100	Power law	BA	8.9	5.3–13.9	8.6	4.1–15.9	✓
	2–13	3–100	Uniform	FGK		<6.9	0.7	0.3–2.9	✓

Notes. The "Mass" and "S.m.a." columns give the ranges of companion masses and semimajor axes, respectively. [a]Compatibility between the results from SHINE and from the previous work. We assumed one asymmetric normal distribution for each measurement, and we tested the null hypothesis that the two measurements are equal with a 5% risk, as described in Appendix D. A check mark indicates that the null hypothesis is accepted, and a cross mark that it is not. [b]The SHINE analysis is always truncated at 300 au. [c]In contrast to confidence intervals that are expressed at 68% confidence level, all upper limits are expressed at 95% confidence level. [d]In Vigan et al. (2012) the sample included only 4 F-stars, therefore we consider that the results are only marginally biased compared to SHINE BA results.

5. Lessons learned & perspectives

Large samples to better explore/confirm the effect of:

- Fill the original bins of masses more than 20 stars per bin,
- Age/Environment (ScoCen versus YMGs?) bin,
- Correlation occurrence system hosting giant planet & hosting “debris” disks?

Current biases:

- Detection limits: statistical robustness,
- Candidates: consider that undefined/ambiguous candidates are background,
- Binaries rejection, probable bias for mass ratio exploration (AF to M dwarfs) for Parametric models.

Population synthesis (what is missing):

- CA,GI for various stellar masses (currently only solar-mass),
- CA including planet-planet interactions

5. Lessons learned & perspectives

Large samples to better explore/confirm the effect of:

- Fill the original bins of masses more than 20 stars per bin,
- Age/Environment (ScoCen versus YMGs?) bin,,
- Correlation occurrence system hosting giant planet & hosting “debris” disks?

F400, BEAST, YSES, FELLOWS, ... COBREX-WP1

Current biases:

- Detection limits: statistical robustness,
- Candidates: consider that undefined/ambiguous candidates are background,
- Binaries rejection, probable bias for mass ratio exploration (AF to M dwarfs) for Parametric models.

PACO, SnapSHINE, Gaia-DR2/3...

Population synthesis (what is missing):

- CA,GI for various stellar masses (currently only solar-mass),
- CA including planet-planet interactions

...

5. Lessons learned & perspectives

Large samples & stellar mass/age bins

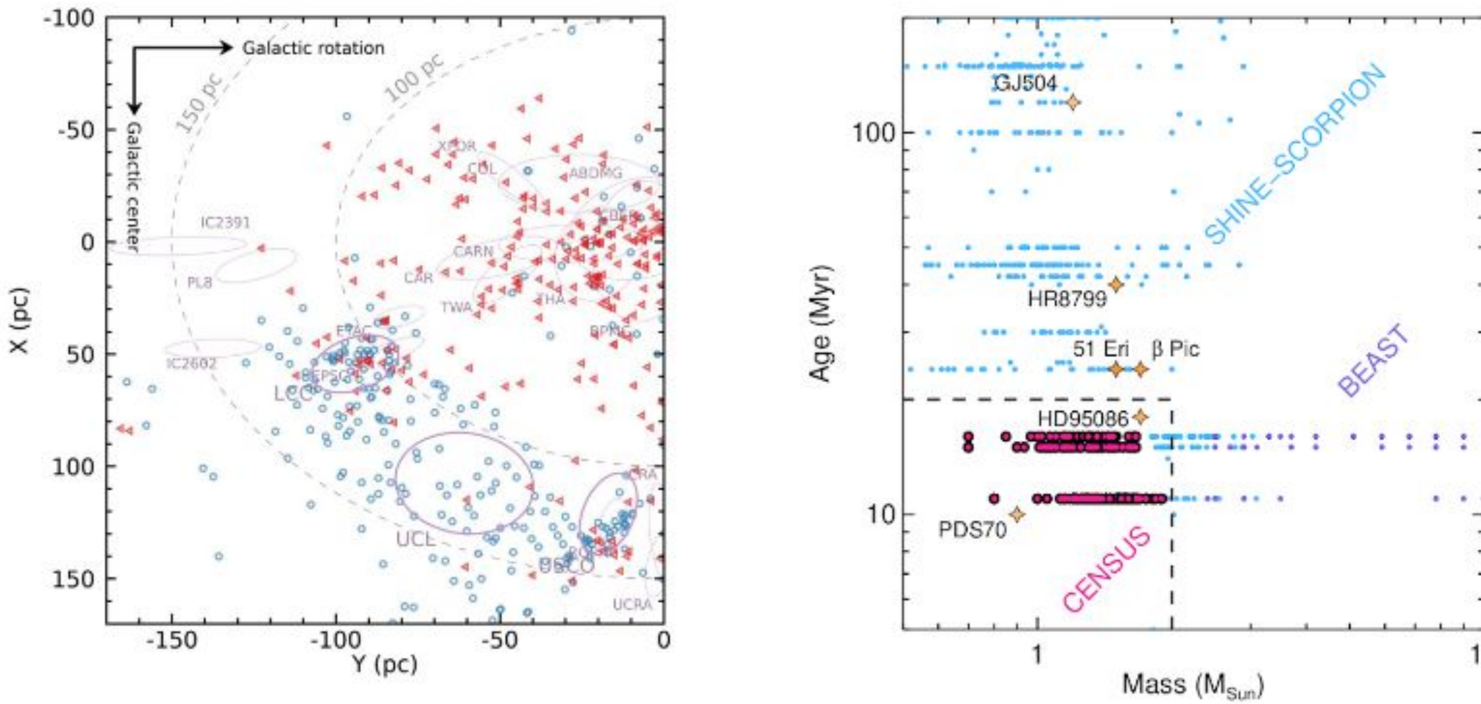


Fig. 1: *Left*, Galactic coordinates XY of the targets from the BEAST, SHINE and SCORPION samples observed with SPHERE in deep imaging, color-coded for BA-types stars (*blue*) and for FGK-type stars (*red*). The location of the nearby associations (TW Hydrae, β Pic, Columba, Tucana-Horologium...) and of the USCO, LCC and UCL sub-regions of Sco-Cen are reported. **Today, the fraction of Sun-like star members of Sco-Cen observed with SPHERE in deep imaging is marginal**. In contrast, they represent the core of the CENSUS Large Programme. *Right*, Age versus mass distribution of the stars observed during the BEAST (*purple*), SHINE-SCORPION (*light blue*) deep imaging campaigns together with CENSUS (*pink*) proposed for exploring a pristine sample of young, FGK-type (0.8-1.8 $M_{\odot}$) members in Sco-Cen. Emblematic known exoplanets are reported to highlight the fact that CENSUS will observe PDS70 and "young" HR8799-analogs.

5. Lessons learned & perspectives

Candidates: F400 status & SnapSHINE follow-up