SPOTS

Search for Planets Orbiting Two Stars

Constraining the frequency of sub-stellar companions on wide circumbinary orbits

Mariangela Bonavita[1,2]

S. Desidera[2], C. Thalmann[3], M. Janson[4], A. Vigan[5], G.Chauvin[6] and J. Lannier[6]

[1]Institute for Astronomy, The University of Edinburgh
[2]Osservatorio Astronomico di Padova, INAF, Italy
[3]Institute for Astronomy, ETH Zurich
[4]Department of Astronomy, Stockholm University
[5]Aix Marseille Université, CNRS, Laboratoire d'Astrophysique de Marseille
[6]Institut de Planétologie et d'Astrophysique de Grenoble, UJF, CNRS

Why (not) Planets in Binaries?

Why (not) Planets in Binaries?

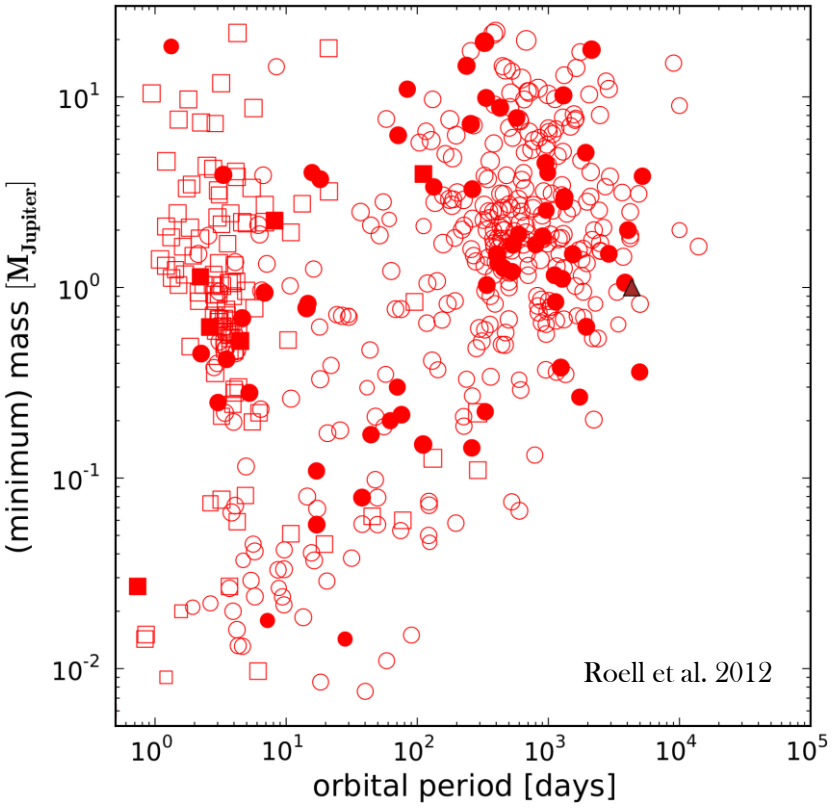
- Unexplored planet population!

Why (not) Planets in Binaries?

- Unexplored planet population!
  - ✓ > 50 % stars are in multiple star systems (Duquennoy & Mayor 1991)

Why (not) Planets in Binaries?

- Unexplored planet population!
  - ✓ > 50 % stars are in multiple star systems (Duquennoy & Mayor 1991)
  - ✓ Several exoplanets hosts have been proved to be part of binary/multiple systems



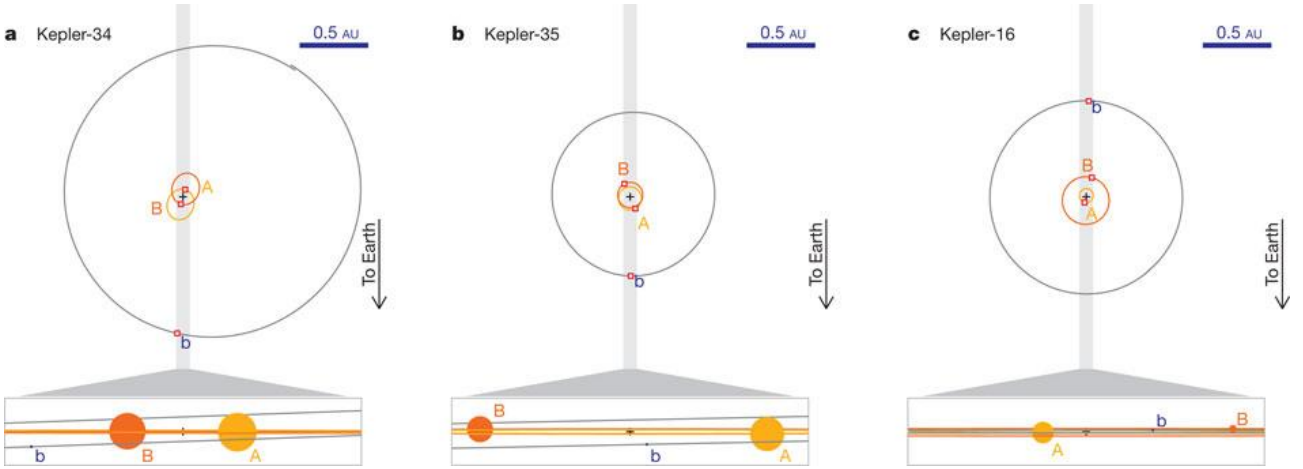
Why (not) Planets in Binaries?

- Unexplored planet population!
  - ✓ > 50 % stars are in multiple star systems (Duquennoy & Mayor 1991)
  - ✓ Several exoplanets hosts have been proved to be part of binary/multiple systems
  - ✓ Most RV and Transit surveys are biased against multiple stars

Why Circumbinary Planets?

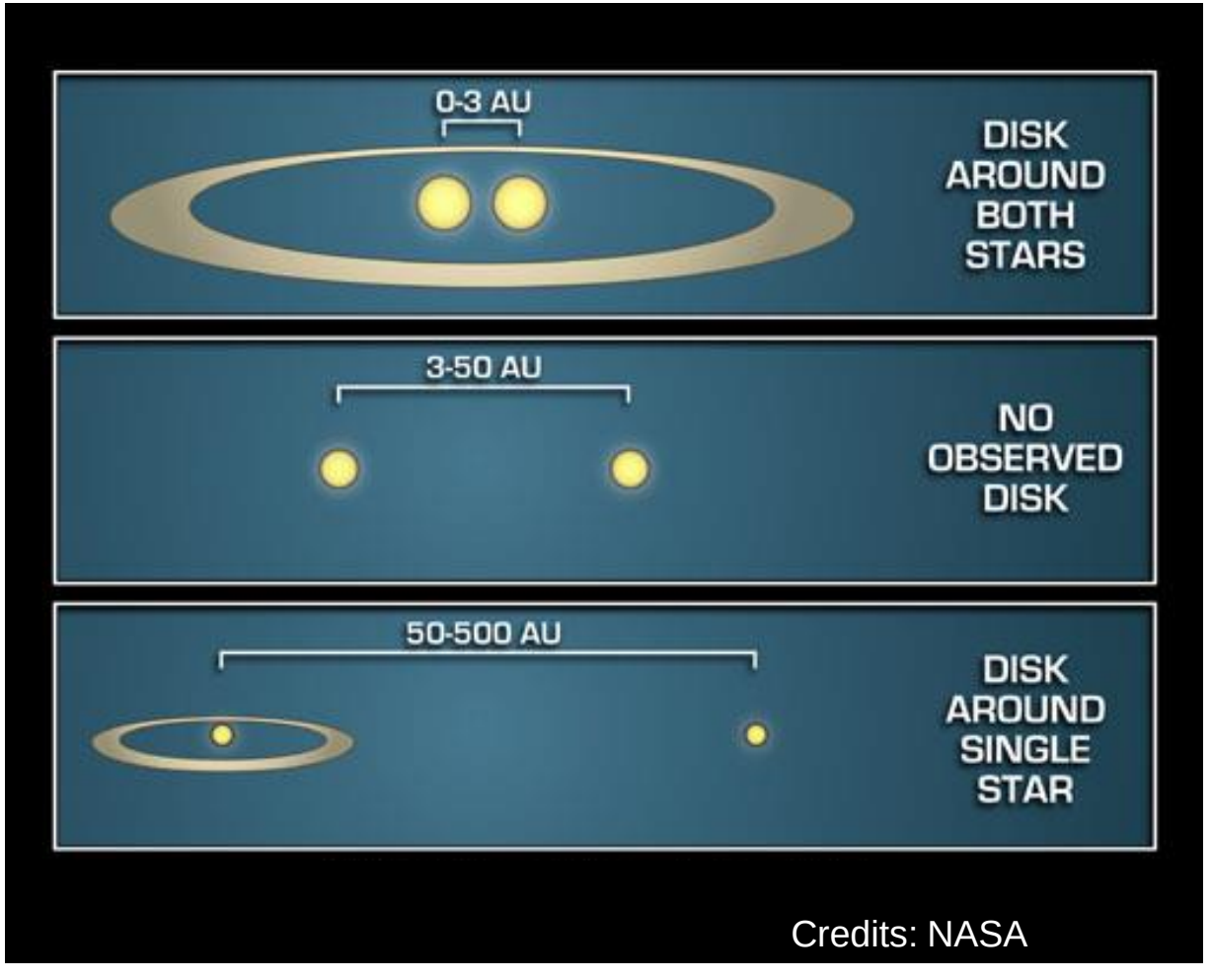
Why Circumbinary Planets?

- **Probably abundant (?)**
  - ✓ ~10 confirmed companions detected with Kepler up to now



Why Circumbinary Planets?

- **Probably abundant (?)**
  - ✓ ~10 confirmed companions detected with Kepler up to now
  - ✓ ~60% of close (<3 AU) binaries show IR excess rate



Credits: NASA

Why Circumbinary Planets?

- **Probably abundant (?)**
  - ✓ ~10 confirmed companions detected with Kepler up to now
  - ✓ ~60% of close (<3 AU) binaries show IR excess rate
  - ✓ Several claims of massive planetary companions to post-common envelope binaries detected via TTV

Why Circumbinary Planets?

- **Probably abundant (?)**
  - ✓ ~10 confirmed companions detected with Kepler up to now
  - ✓ ~60% of close (<3 AU) binaries show IR excess rate
  - ✓ Several claims of massive planetary companions to post-common envelope binaries detected via TTV

- **Well suited for detection with Direct Imaging**
  - ✓ Unlike RV and Transits, Direct Imaging is mostly sensitive to planets on wide orbits
  - ✓ Few planetary mass companions already imaged so far

The SPOTS Survey

First direct imaging survey dedicated to circumbinary planets

The SPOTS Survey

First direct imaging survey dedicated to circumbinary planets

- VLT/NaCo Pilot Survey
  - ✓ 26 Targets
  - ✓ 10 candidates
  - ✓ No confirmed co-moving companions

The SPOTS Survey

First direct imaging survey <u>dedicated to circumbinary planets</u>

- ❑VLT/NaCo Pilot Survey
  - ✓ 26 Targets
  - ✓ 10 candidates
  - ✓ No confirmed co-moving companions

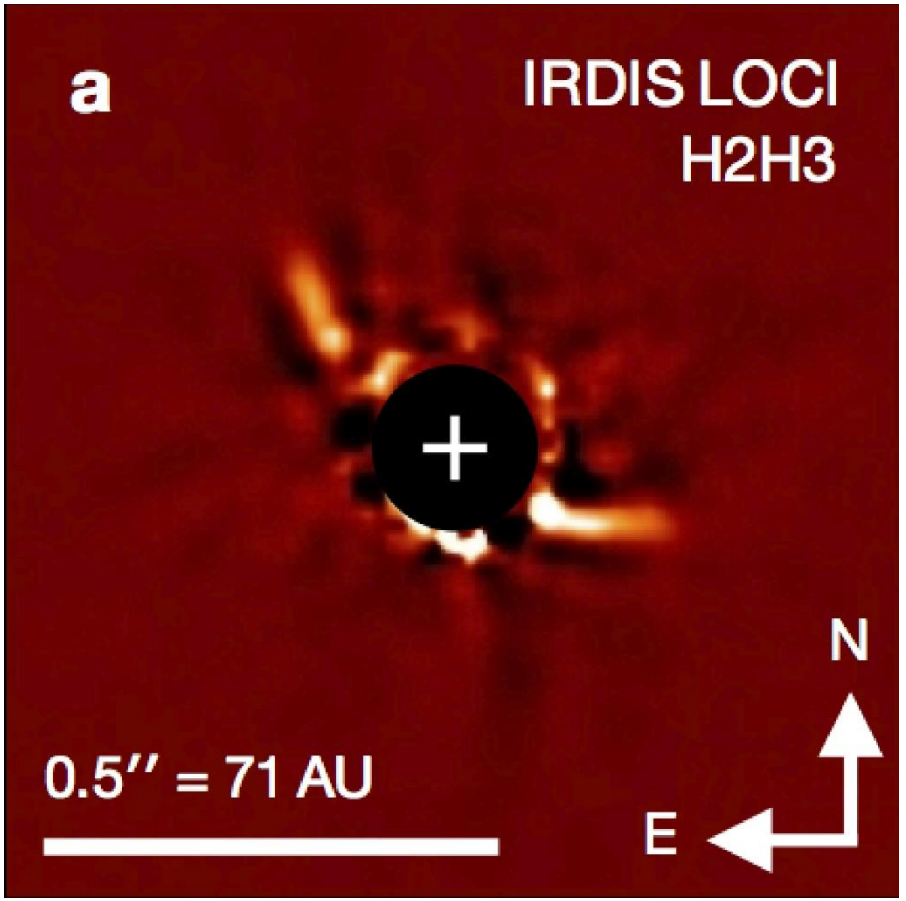
- ❑VLT/SPHERE Full Survey
  - ✓ 40 Targets
  - ✓ Several candidates

The SPOTS Survey

First direct imaging survey <u>dedicated to circumbinary planets</u>

- ❑VLT/NaCo Pilot Survey
  - ✓ 26 Targets
  - ✓ 10 candidates
  - ✓ No confirmed co-moving companions

- ❑VLT/SPHERE Full Survey
  - ✓ 40 Targets
  - ✓ Several candidates
  - ✓ 1 resolved circumbinary disk (AK Sco)



Janson et al. 2016

SPOTS II - Constraints from the literature: Stellar Samples

SPOTS II - Constraints from the literature: Stellar Samples

- **Circumbinary (CBIN) Sample**
  - **24 Published Direct Imaging Surveys**

SPOTS II - Constraints from the literature: Stellar Samples

❑ Circumbinary (CBIN) Sample

- **24 Published Direct Imaging Surveys**

Table 1: Characteristics of the surveys considered to build the **circumbinary (CBIN) sample. Both the total number of targets included in each survey (N_{Srv}) and the number of stars considered in our study (N_{CBIN}) are reported.**

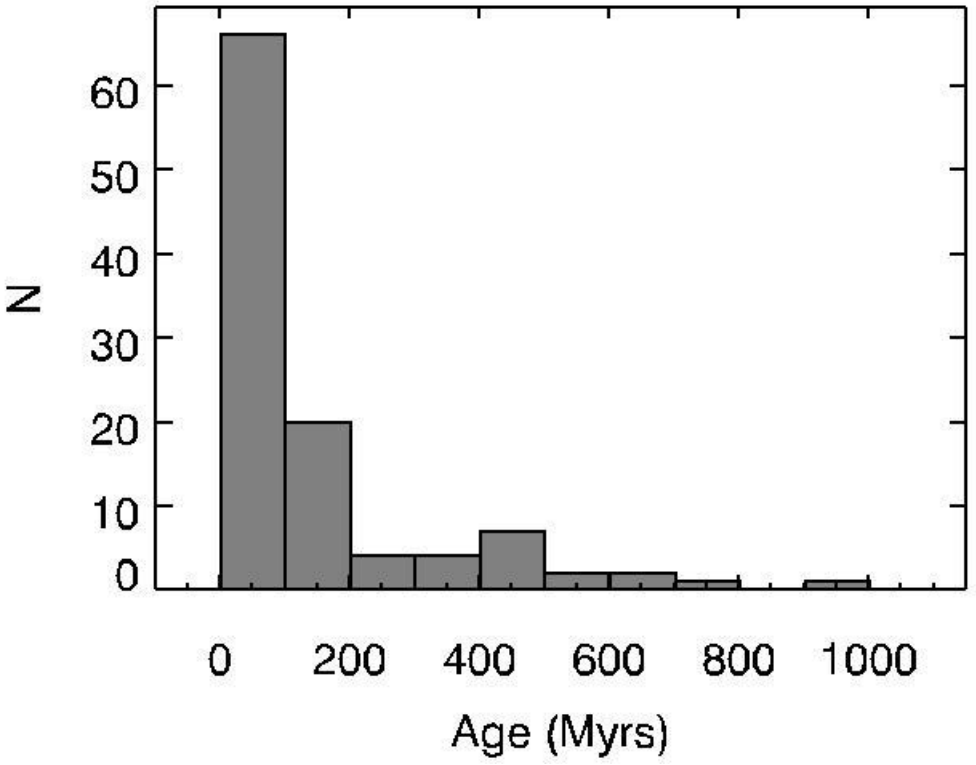
Source	Instrument	Technique	Filter	N_{Srv}	N_{CBIN}	Reference
L05	HST/NICMOS	COR	H(1.4-1.8)	45	6	Lowrance et al. (2005)
B06	VLT/NACO	COR	K_S/H	17	3	Brandeker et al. (2006)
B07	VLT-NACO/MMT	SDI	H	45	7	Biller et al. (2007)
K07	VLT/NACO	DI	L	22	4	Kasper et al. (2007)
GDPS	GEMINI/NIRI	SDI	H	85	8	Lafrenière et al. (2007)
CH10	VLT/NACO	COR	H/K_S	91	9	Chauvin et al. (2010)
H10	Clio/MMT	ADI	L'/M	54	3	Heinze et al. (2010)
JB11	GEMINI/NIRI	ADI	K/H	18	3	Janson et al. (2011)
JJ12	VLT/NACO	DI	K_S	1	1	Joergens et al. (2012)
V12	VLT/NACO, NIRI	ADI	K_S/H'/CH4	42	3	Vigan et al. (2012)
R13	VLT/NACO	ADI	L'	59	3	Rameau et al. (2013b)
B13	SUBARU/HiCiao	DI/ADI/PDI	H	63	6	Brandt et al. (2014a)
J13	SUBARU/HiCiao	ADI	H	50	4	Janson et al. (2013a)
Y13	SUBARU/HiCiao	ADI	H/K_S	20	3	Yamamoto et al. (2013)
N13	GEMINI/NICI	ADI/ASDI	H	70	4	Nielsen et al. (2013)
BN13	GEMINI/NICI	ADI/ASDI	H	80	4	Biller et al. (2013)
JL13	GEMINI/NICI	DI/ADI	K_S	138	5	Janson et al. (2013b)
L14	GEMINI/NIRI	DI/ADI	K_S	91	18	Lafrenière et al. (2014)
SONG	HST	ADI	H	116	14	Song et al. priv. comm.
M14	VLT/NACO	ASDI	H	16	1	Maire et al. (2014)
NLP	VLT/NACO	DI/ADI	H	110	8	Chauvin et al. (2015)
D15	GEMINI/NIRI	DI	K_S	64	4	Daemgen et al. (2015)
B15	SUBARU/HiCiAO	DI/ADI	K_S	31	5	Bowler et al. (2015)
	KECK/NIRC2/N	DI/ADI	H	59	3	
L15	VLT/NACO	ADI	L'	58	10	Lannier et al. 2016 (submitted)

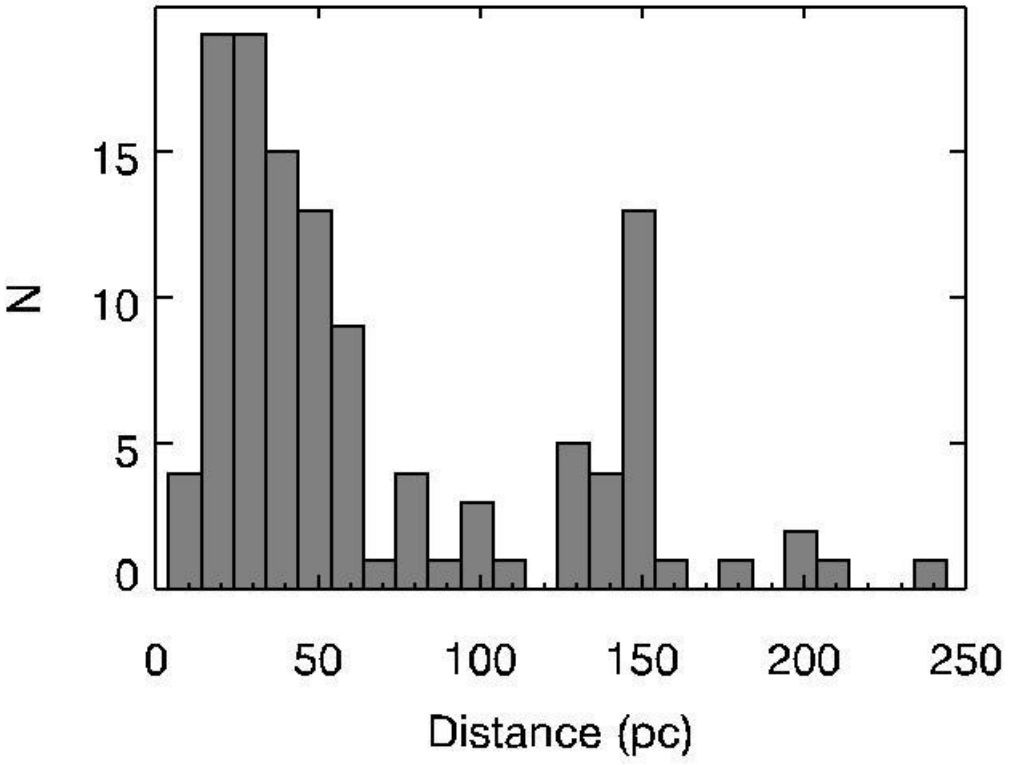
Techniques: **COR** = Coronagraphy; **SDI** = Spectral Differential Imaging; **DI** = Direct Imaging; **ADI** = Angular Differential Imaging; **PDI** = Polarized Differential Imaging; **ASDI** = Angular and Spectral Differential Imaging

Bonavita et al. 2016 A&A Submitted

SPOTS II - Constraints from the literature: Stellar Samples

- **Circumbinary (CBIN) Sample**
  - **24 Published Direct Imaging Surveys**
  - **117 Systems**
    - ✓86 binaries
    - ✓31 higher order multiples

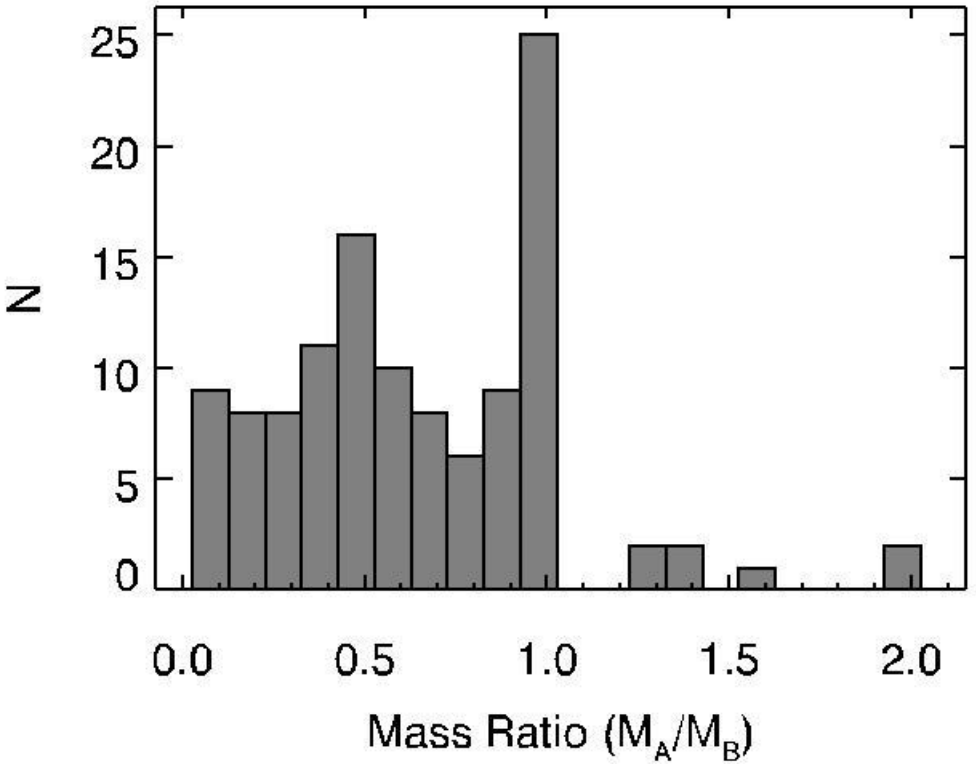


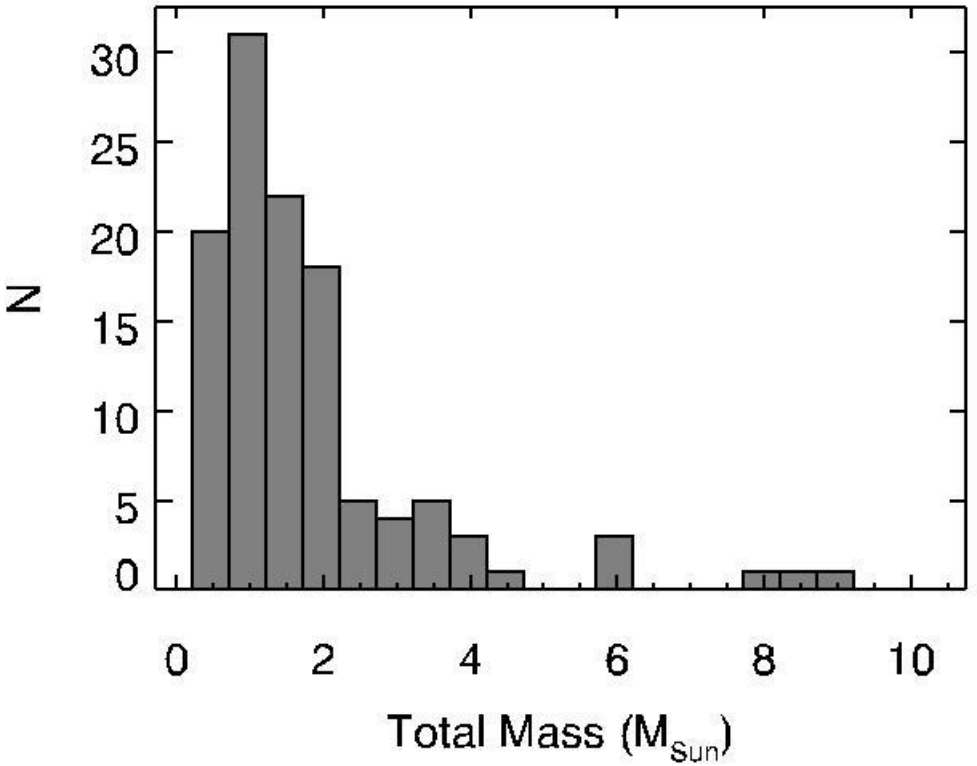


Bonavita et al. 2016 A&A Submitted

SPOTS II - Constraints from the literature: Stellar Samples

- **Circumbinary (CBIN) Sample**
  - **24 Published Direct Imaging Surveys**
  - **117 Systems**
    - ✓86 binaries
    - ✓31 higher order multiples

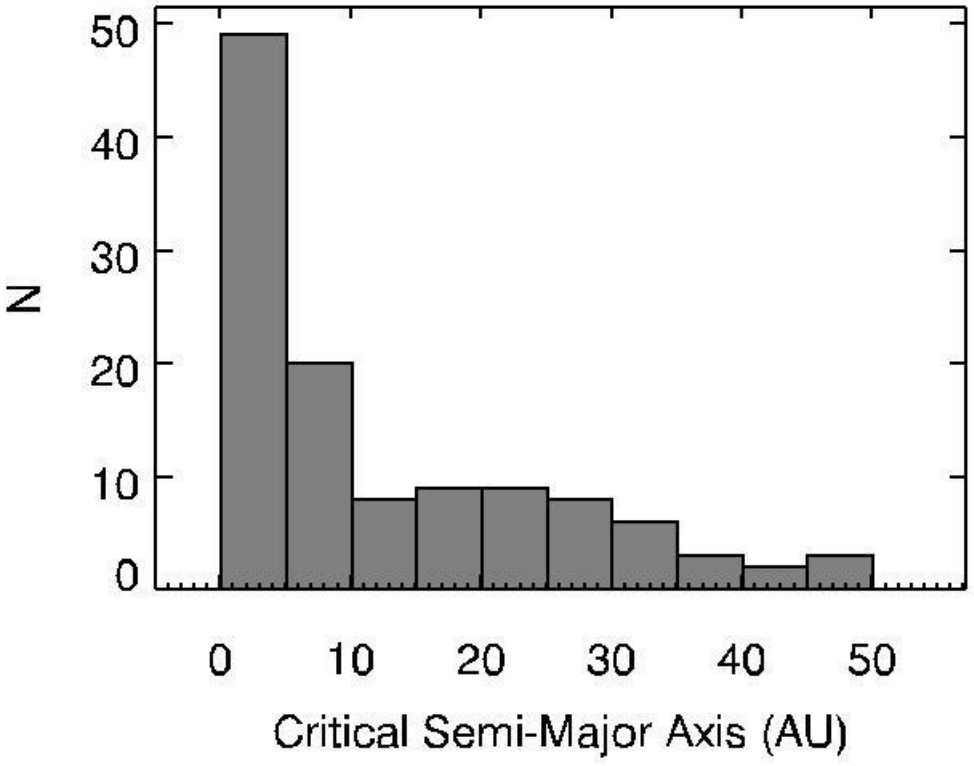


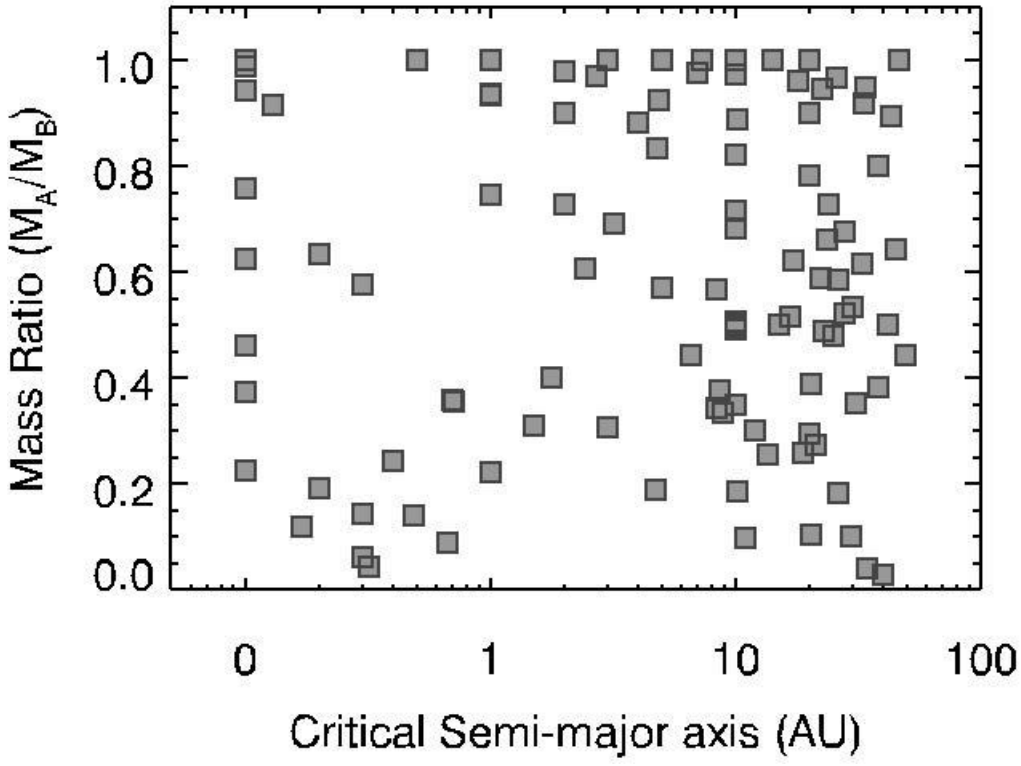


Bonavita et al. 2016 A&A Submitted

SPOTS II - Constraints from the literature: Stellar Samples

- **Circumbinary (CBIN) Sample**
  - **24 Published Direct Imaging Surveys**
  - **117 Systems**
    - ✓86 binaries
    - ✓31 higher order multiples





SPOTS II - Constraints from the literature: Stellar Samples

❑ Circumbinary (CBIN) Sample

- **24 Published Direct Imaging Surveys**
- **117 Systems**
  - ✓86 binaries
  - ✓31 higher order multiples
- **5 Detections**
  - ✓2 planetary mass companions
  - ✓3 low-mass brown dwarfs

Name	Mass	Separation
HIP 59960 b	11 M_{Jup}	654 AU
2MASS J0103 AB b	13 M_{Jup}	84 AU
TWA 5 B	20 M_{Jup}	127 AU
HIP 19176 B	32 M_{Jup}	400 AU
H II 1348 B	56 M_{jup}	145 AU

SPOTS II - Constraints from the literature: Stellar Samples

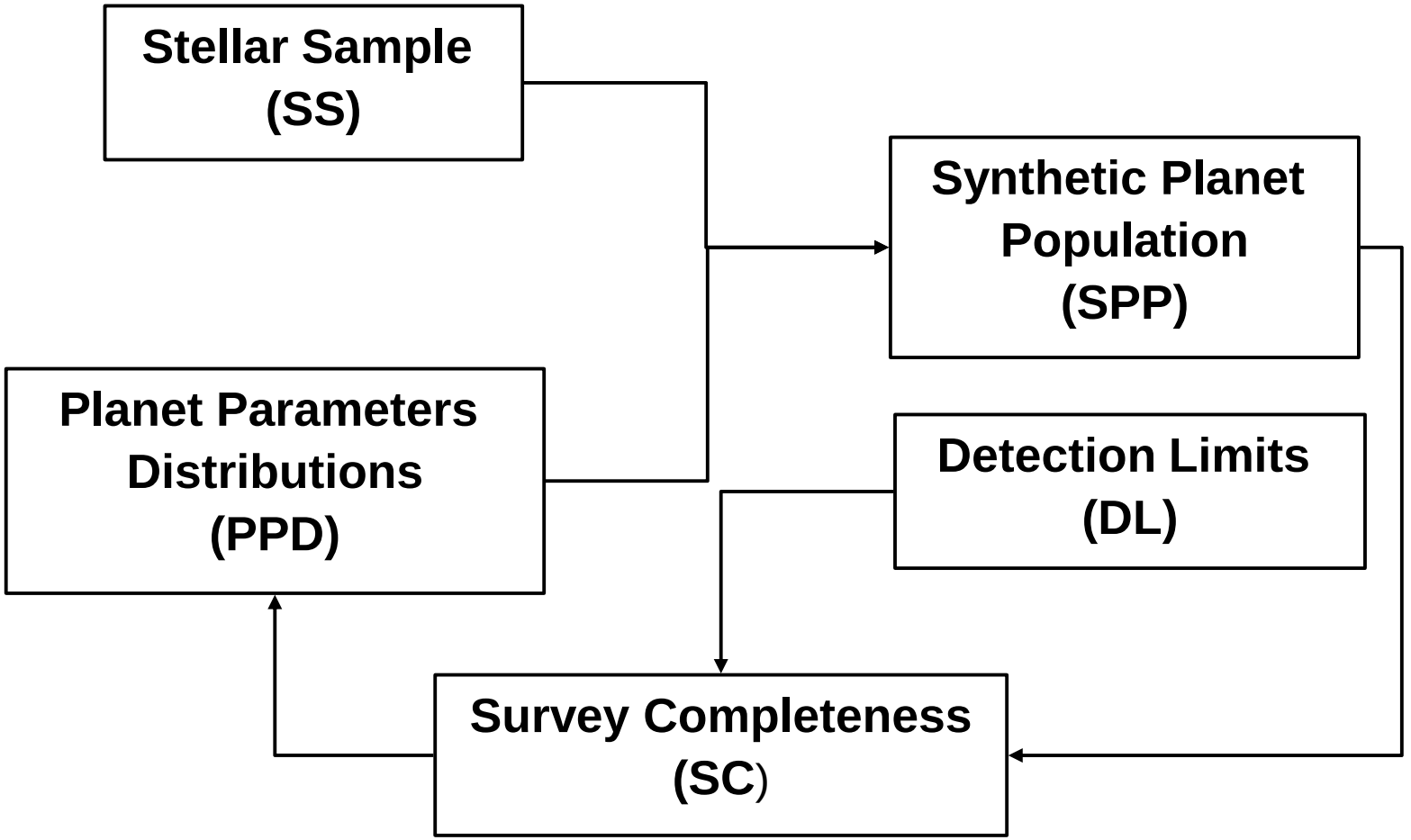
- **Circumbinary (CBIN) Sample**
  - **24 Published Direct Imaging Surveys**
  - **117 Systems**
    - ✓86 binaries
    - ✓31 higher order multiples
  - **5 Detections**
    - ✓2 planetary mass companions
    - ✓3 low-mass brown dwarfs

- **Single Stars (SS) Control Sample**
  - **205 Single stars and wide binaries** from the Brandt et al. 2014 paper
  - **7 Detections**
    - ✓ 2 planetary mass companions
    - ✓ 5 low-mass brown dwarfs

SPOTS II - Constraints from the literature: Statistical Analysis

SPOTS II - Constraints from the literature: Statistical Analysis

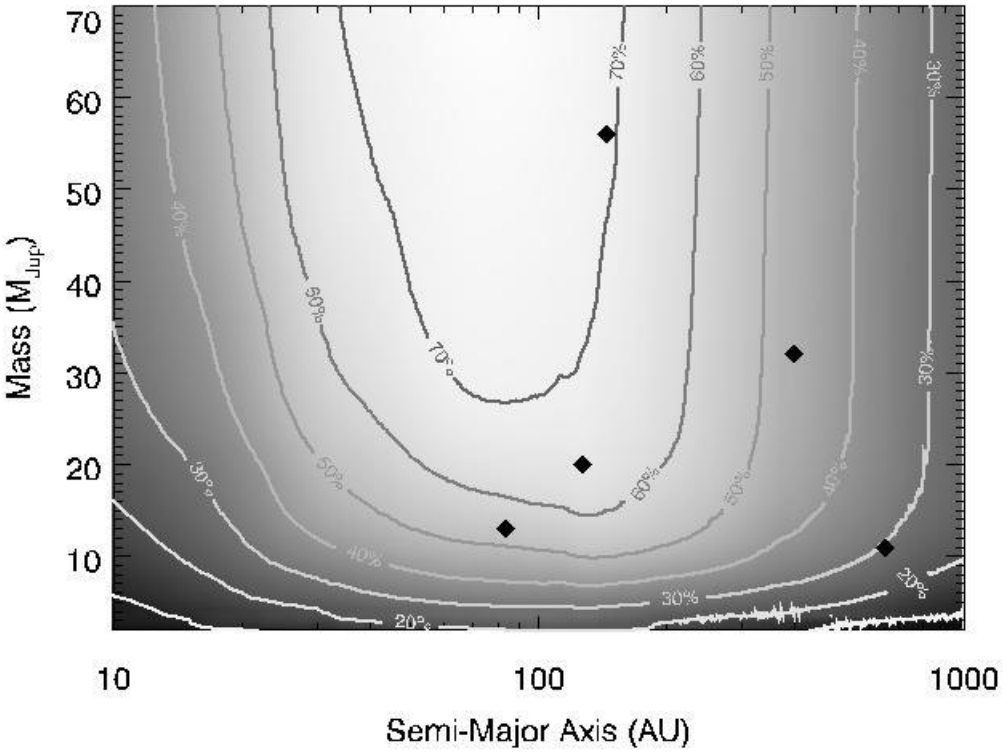
- The Q-MESS Code (Bonavita et al. 2013) was used to estimate the survey detection probability fp_j



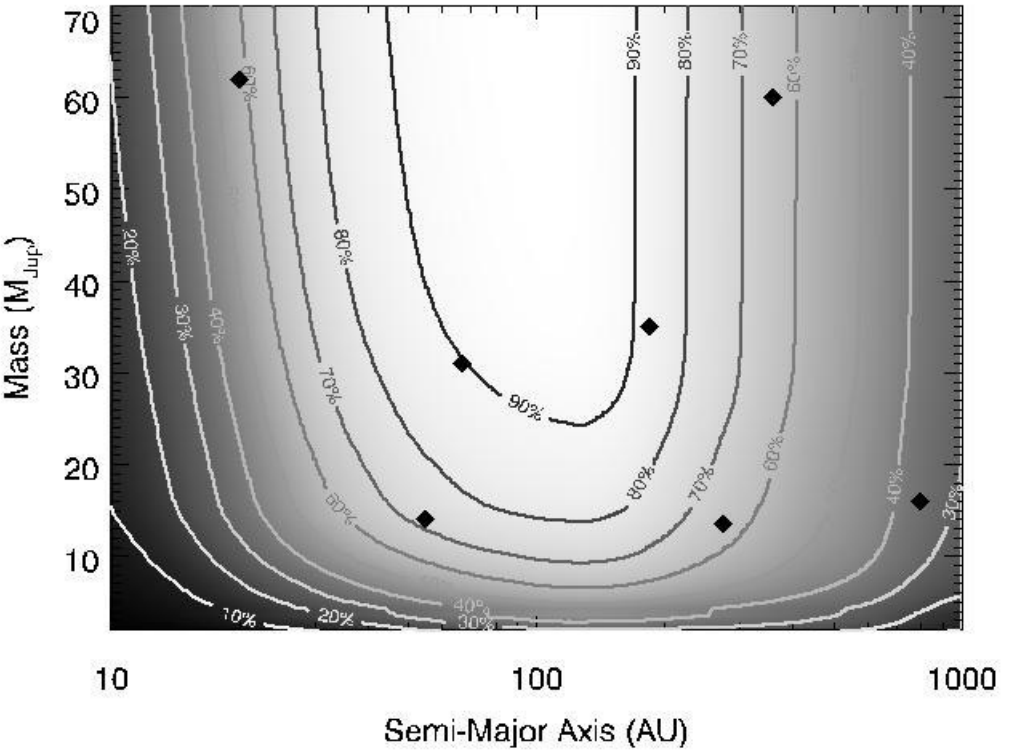
SPOTS II - Constraints from the literature: Statistical Analysis

- The Q-MESS Code (Bonavita et al. 2013) was used to estimate the survey detection probability fp_j

CBIN Sample



SS Sample



Bonavita et al. 2016 A&A Submitted

SPOTS II - Constraints from the literature: Statistical Analysis

- The Q-MESS Code (Bonavita et al. 2013) was used to estimate the survey detection probability fp_j

- This was then used to constrain the probability distribution $p\left(f\left\{\middle| d_j\right\}\right)$ of the companion frequency f, given the detections d_j, for a given range of mass and semi-major axis, at a given confidence level α

SPOTS II - Constraints from the literature: Statistical Analysis

- The Q-MESS Code (Bonavita et al. 2013) was used to estimate the survey detection probability fp_j

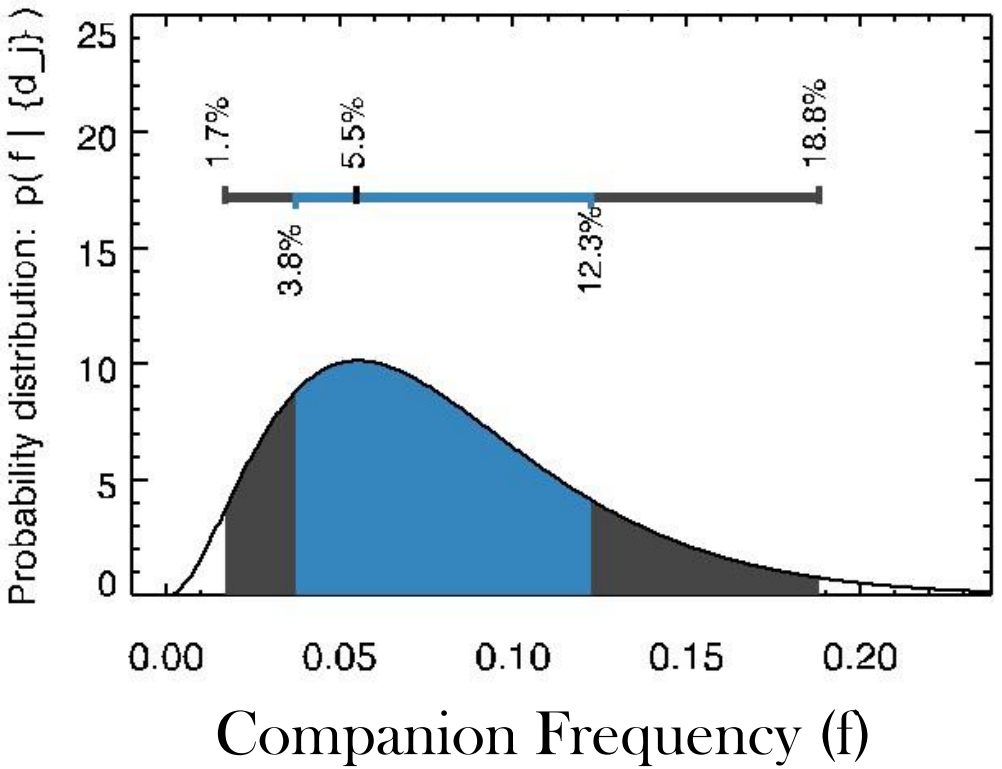
- This was then used to estimate the probability distribution $p\left(f\left\{\left|d_j\right.\right\}\right)$ of the companion frequency f, given the detections d_j, for a given range of mass and semi-major axis, at a given confidence level α

- Finally we calculated the confidence interval $[f_{min}, f_{max}]$ so that: $\alpha = \int_{f_{min}}^{f_{max}} p\left(f\left\{\left|d_j\right.\right\}\right) df$

SPOTS II - Constraints from the literature: Results

- **Frequency of wide (< 1000 AU) circumbinary companions:**
  - ✓ Planets (2-14 M_{jup}) : $f \in [1.7, \% 18.8\%]$

Planetary mass companions

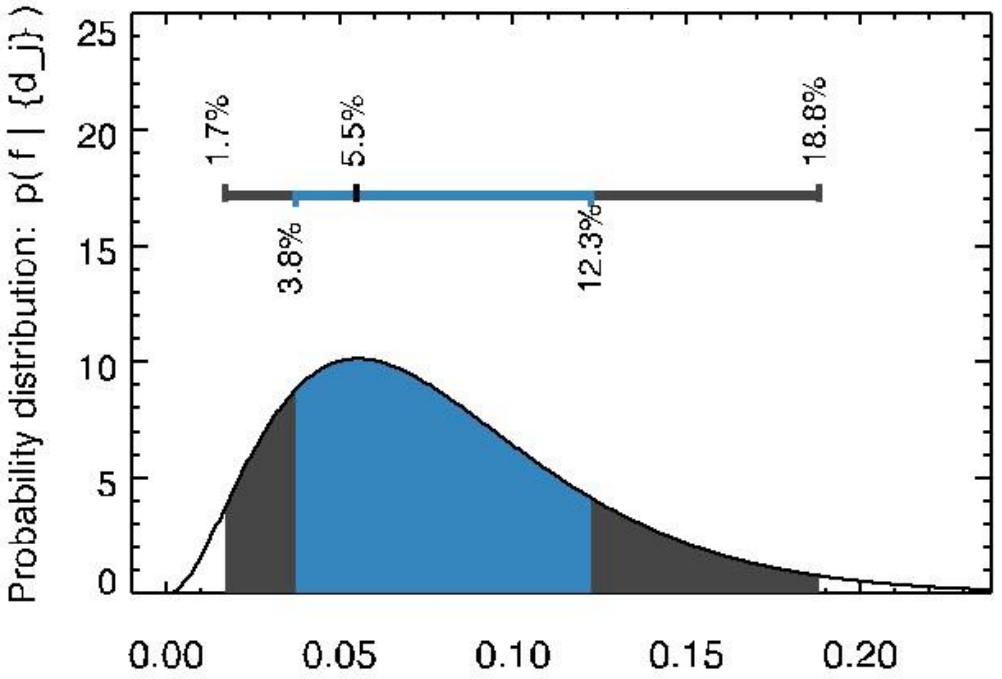


Bonavita et al. 2016 A&A Submitted

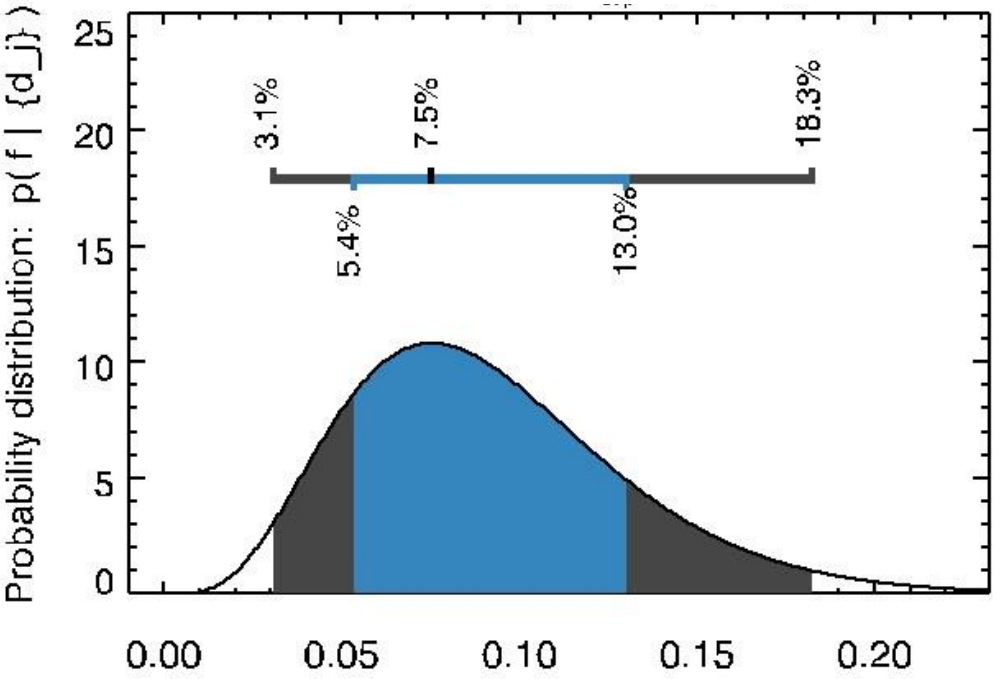
SPOTS II - Constraints from the literature: Results

- **Frequency of wide (< 1000 AU) circumbinary companions:**
  - ✓ Planets (2-14 M_{jup}) : $f \in [1.7\%, 18.8\%]$
  - ✓ Planets + Brown Dwarfs (2-70 M_{jup}) : $f \in [3.1\%, 18.3\%]$

Planetary mass companions



All sub-stellar companions



Bonavita et al. 2016 A&A Submitted

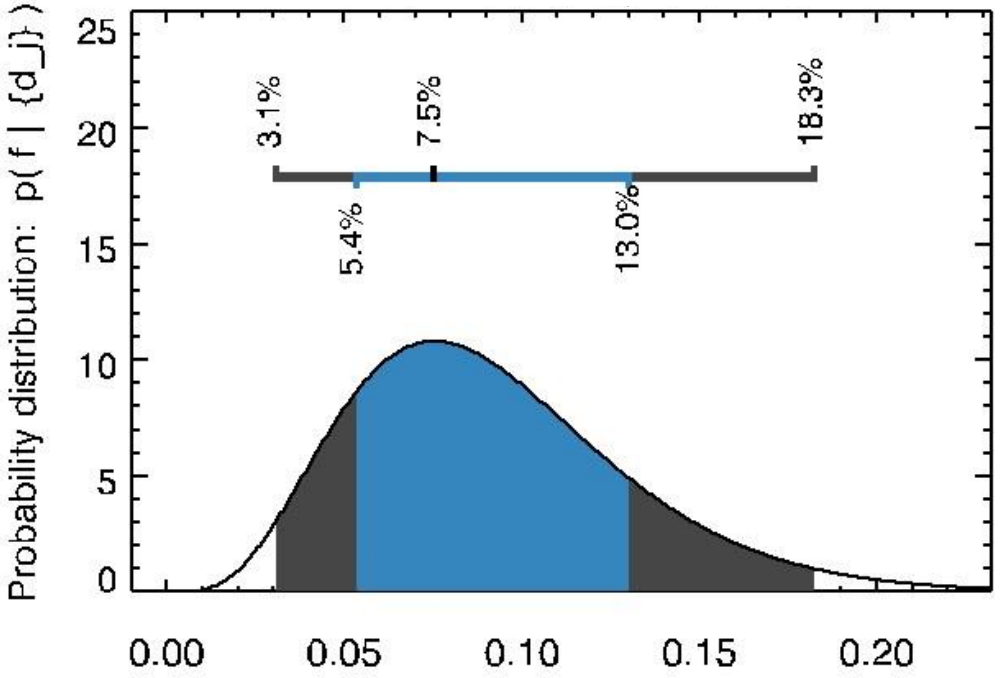
SPOTS II - Constraints from the literature: Results

- Our observations are compatible with a frequency of wide (< 1000 AU) circumstellar companions up to 70 M_{Jup} between ~3% and ~18%

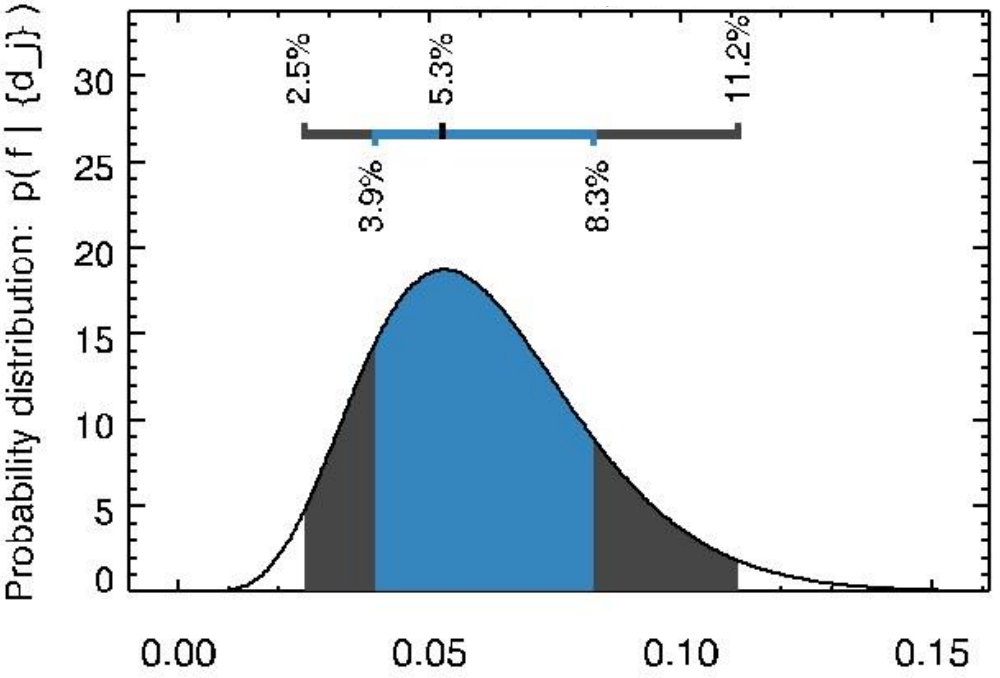
SPOTS II - Constraints from the literature: Results

- **Our observations are compatible with a frequency of wide (< 1000 AU) circumstellar companions up to 70 M_{Jup} between ~3% and ~18%**
  - ✓ These values are in agreement with the frequency of companions around single stars

CBIN Sample



SS Sample



SPOTS II - Constraints from the literature: Results

- **Our observations are compatible with a frequency of wide (< 1000 AU) circumstellar companions up to 70 M_{Jup} between ~3% and ~18%**
  - ✓ These values are in agreement with the frequency of companions around single stars
  - ✓ Such values also seem to point toward a second generation formation scenario for the planets around post-common envelope binaries

SPOTS II - Constraints from the literature: Results

- **Our observations are compatible with a frequency of wide (< 1000 AU) circumstellar companions up to 70 M_{Jup} between ~3% and ~18%**
  - ✓ These values are in agreement with the frequency of companions around single stars
  - ✓ Such values also seem to point toward a second generation formation scenario for the planets around post-common envelope binaries

- **Our sample includes binaries similar to those targeted by Kepler but:**
  - ✓ Most DI companions are very far from the stability limit

Name	Mass	Separation	Stability Limit
HIP 59960 b	11 M_{Jup}	654 AU	~2 AU
2MASS J0103 AB b	13 M_{Jup}	84 AU	~43 AU
TWA 5 B	20 M_{Jup}	127 AU	~ 12 AU
HIP 19176 B	32 M_{Jup}	400 AU	~ 40 AU
H II 1348 B	56 M_{jup}	145 AU	~ 10 AU

SPOTS II - Constraints from the literature: Results

- **Our observations are compatible with a frequency of wide (< 1000 AU) circumstellar companions up to 70 M_{jup} between ~3% and ~18%**
  - ✓ These values are in agreement with the frequency of companions around single stars
  - ✓ Such values also seem to point toward the second generation formation scenario for the planets around post-common envelope binaries

- Our sample includes binaries similar to those targeted by Kepler but:
  - ✓ Most DI companions are very far from the stability limit
  - ✓ Constraints on the binary orbits are not good enough

SPOTS II - Constraints from the literature: Conclusions

- There's no strong difference, in terms of the frequency of wide sub-stellar companions, between close binaries and single stars

- Such low companion frequency seems to favour the second generation scenario for planets around post-common envelope binaries

- Further information is needed to clarify whether the DI circumbinary planets and the Kepler ones belong to a different population

Why Circumbinary Planets?

- **Probably abundant (?)**
  - ✓ ~10 confirmed companions detected with Kepler up to now
  - ✓ ~60% of close (<3 AU) binaries show IR excess rate
  - ✓ Several claims of massive planetary companions to post-common envelope binaries detected viaTTV

- **Well suited for detection with Direct Imaging**
  - ✓ Unlike RV and Transits, Direct Imaging is mostly sensitive to planets on wide orbits
  - ✓ Few planetary mass companions detected so far

- **Could provide insights into planet formation**
  - ✓ Dependence of the planet mass/frequency on the disk mass (2 G-type = 1 A-type?)
  - ✓ Dynamical effects shaping the planetary systems