Data Analysis and Preliminary Results of the JouFLU Exozodi Survey

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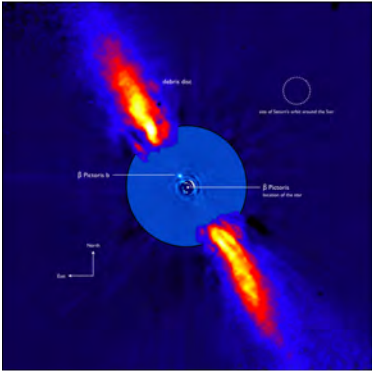
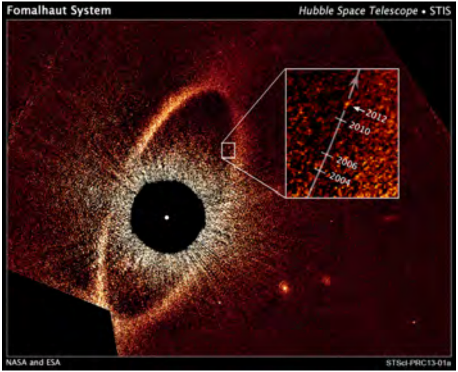
Towards direct imaging in the habitable zone

Beta-Pictoris b at $\lambda = 3.5\,\mu m$



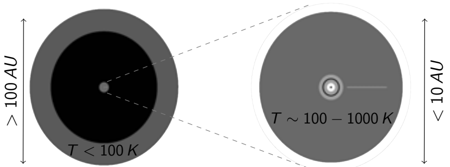
$D \approx 8\,AU$, $\theta_{sep} \approx 0.5''$
(Lagrange et al. 2009)

Fomalhaut b at $\lambda = 0.6\,\mu m$



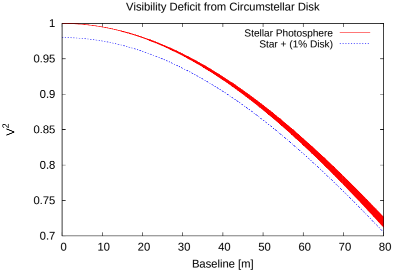
$D \approx 116\,AU$, $\theta_{sep} \approx 15''$
(Kalas et al. 2008)

Hot Circumstellar Dust in Main Sequence Stars



Cold Debris Disk
$\theta > 100''$ at 10 pc

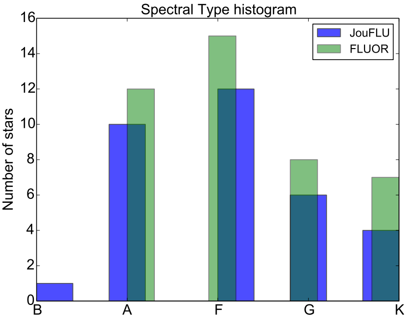
Hot Dust Disk
$\theta \sim 0.1''$ at 10 pc

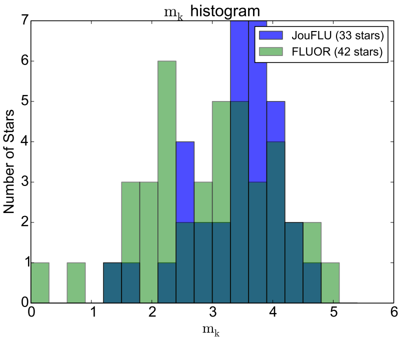


- Must be understood to ensure success of future direct imaging missions
- Can be used to learn about planet formation & dynamical state
- Hot dust (K band) is detected in a 25% fraction of main sequence stars (Absil et al. 2013). 12% in H-Band (Ertel, + 2014)
- Generally a $\sim 1\%$ deficit in visibility.

K-Band Observations after 2012

37 new stars, 14 follow-ups (See N. Scott's talk), 4 LBTI list



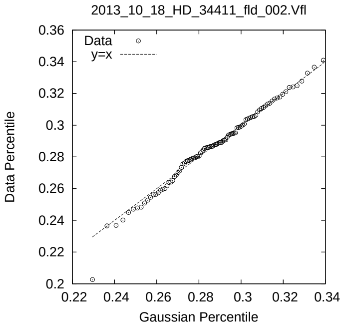


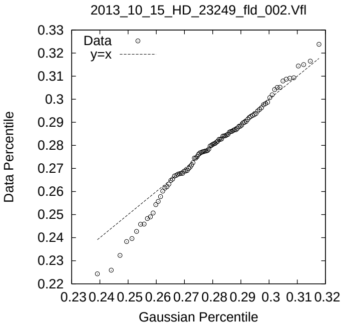
Total of 79 stars: 21 with a known outer cold reservoir.

Nominally 3 calibrators per target.

Data reduction: Unbiased Visibility Estimators

- The FLUOR/CLASSIC pipeline offers several unbiased estimators, e.g. V_NORM, V_SQRT, V_LOGNORM
- All of the current estimators assume that the measured Visibility follows Gaussian statistics (?)





Data are not always Gauss distributed

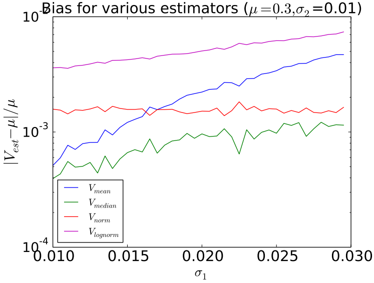
The Median as an unbiased estimator

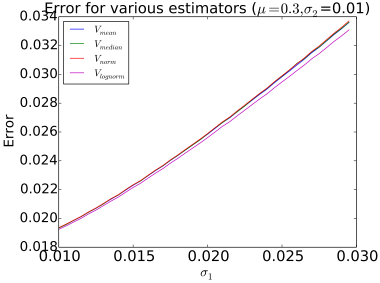
For each fringe scan we measure

$$V^2 = (\mu + N_1)^2 + N_2,$$

where N_1 and N_2 are noise sources (e.g. piston and photon noise).

- If $N_2 = 0$ and $Med(N_1) = 0 \quad \Rightarrow \boxed{\sqrt{Med(V^2)} = \mu}$
- In general, $V_{median} = \sqrt{Med(V^2)}$ has a smaller bias than other estimators





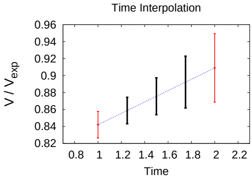
Visibility Calibration

Problem: to estimate V from μ, raw calibrator visibilieits V_1, and V_2, and calibrator expected visibilities $V_{1_{exp}}$, $V_{2_{exp}}$

$$V = \mu \left\{ \alpha_1 \frac{V_{1_{exp}}}{V_1} + \alpha_2 \frac{V_{2_{exp}}}{V_2} \right\} \frac{1}{\alpha_1 + \alpha_2}$$

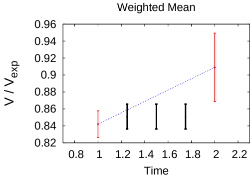
Time Interpolation

$$\alpha_1(t) = \left(\frac{t_2 - t}{t_1 - t_2} \right); \qquad \alpha_2(t) = \left(\frac{t - t_1}{t_1 - t_2} \right)$$



Weighted Mean

$$\alpha_1 = \frac{1}{\sigma_1^2}; \qquad \alpha_2 = \frac{1}{\sigma_2^2}$$



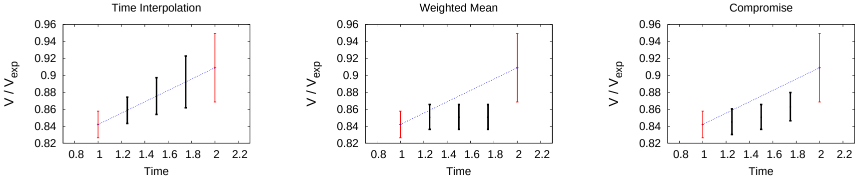
Hybrid Visibility Calibration: a compromise

Maximize prob to obtain co-Transfer function T at time t

$$\mathcal{P}(T, t_1) \sim \exp \underbrace{\left(\frac{-(T - T_1)^2}{2\sigma_1^2} \right)}_{\chi_1^2}; \qquad \mathcal{P}(T, t_2) \sim \exp \underbrace{\left(\frac{-(T - T_2)^2}{2\sigma_2^2} \right)}_{\chi_2^2}$$

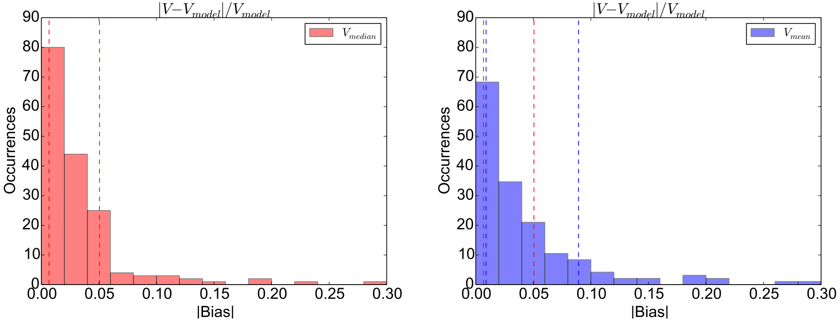
$$\mathcal{P}(T, t) \sim \exp \left\{ \left(\frac{t_2 - t}{t_1 - t_2} \right) \chi_1^2 + \left(\frac{t - t_1}{t_1 - t_2} \right) \chi_2^2 \right\}$$

$$\Rightarrow \boxed{\alpha_1(t) = \frac{1}{\sigma_1^2} \left(\frac{t_2 - t}{t_1 - t_2} \right)} \quad \boxed{\alpha_2(t) = \frac{1}{\sigma_2^2} \left(\frac{t - t_1}{t_1 - t_2} \right)}$$



Testing with JouFLU data: 166 points of non-excess stars

Compared V_{median} with Hybrid interpolation to other approaches: Found smaller bias and uncertainty with the new visibility estimation method.

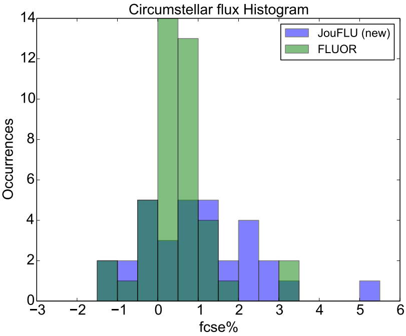


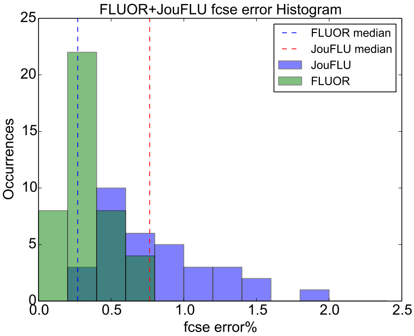
Circumstellar Flux Excess? (6-7 new detections. Preliminary)

Red=Absil 2013 excess. Dust Binarity

Name	ID	m_k	Type	χ^2_{UD}	$f_{csf}/f_\star$	χ^2_{csf}	N_{data}
V* del Eri	HD23249	1.13	K1III-IV C	1.40	$1.44 \pm 1.12\%$	0.10	2
Regulus	HD87901	1.62	B8IVn C	0.35	$0.00 \pm 0.98\%$	0.51	3
ksi boo	HD131156	1.97	G7Ve	1.37	$-0.24 \pm 0.46\%$	1.617	5
40 Eri	HD26965	2.41	K0.5V C	2.07	$0.73 \pm 0.48\%$	2.12	6
kap crb	HD142091	2.49	K0III	4.27	$3.30 \pm 0.6\%$	0.97	10
del Aql	HD182640	2.54	F1IV-V(n)	40.88	$7.1 \pm 0.40\%$	3.90	5
gam ser	HD142860	2.62	F6IV	4.99	$1.70 \pm 0.33\%$	2.47	9
iot per	HD19373	2.64	F9.5V C	1.85	$-0.35 \pm 0.27\%$	1.91	4
iot Pcs	HD222368	2.75	F7V C	4.61	$1.29 \pm 0.25\%$	1.46	8
ups and	HD9826	2.84	F9V C	6.84	$3.03 \pm 0.49\%$	0.73	6
zet aql	HD177724	2.88	A0IV	2.02	$1.22 \pm 0.39\%$	0.95	8
eta lep	HD40136	2.90	F2V C	1.97	$0.75 \pm 0.50\%$	1.90	4
HR 8832	HD219134	3.25	K3V C	0.98	$0.37 \pm 0.55\%$	1.07	7
lam aur	HD34411	3.27	G1V C	1.73	$1.1 \pm 0.39\%$	0.48	6
V* kap01 Cet	HD20630	3.27	G5Vv C	1.24	$1.58 \pm 0.94\%$	0.71	4
tet peg	HD210418	3.30	A1Va C	4.95	$2.2 \pm 0.59\%$	1.79	4
72 oph	HD165777	3.42	A5V C	1.76	$3.53 \pm 1.28\%$	1.46	10
37 and	HD5448	3.49	A5V C	5.24	$2.94 \pm 0.5\%$	0.50	7
HR 6636	HD162003	3.50	F5IV-V C	28.02	$7.06 \pm 0.60\%$	1.67	5
b Aql	HD182572	3.53	G8IV	1.67	$0.93 \pm 0.71\%$	1.73	9
zet ser	HD164259	3.64	F2V C	2.37	$0.21 \pm 0.98\%$	2.66	7
alf lac	HD213558	3.75	A1V C	0.53	$-0.50 \pm 1.02\%$	0.61	4
LTT 15404	HD168151	3.94	F5V C	2.21	$0.08 \pm 0.71\%$	2.70	5
gam tri	HD14055	3.95	A1Vnn C	1.48	$-0.50 \pm 1.18\%$	1.32	3
51 peg	HD217014	3.99	G2.5IVa C	1.00	$-0.29 \pm 0.74\%$	1.16	4

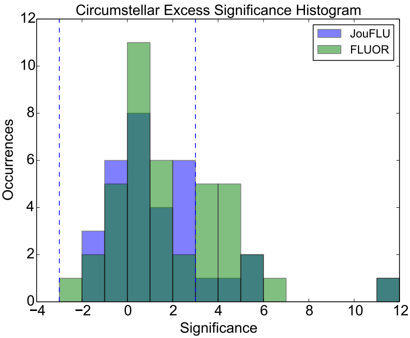
Distributions of Signals and Errors

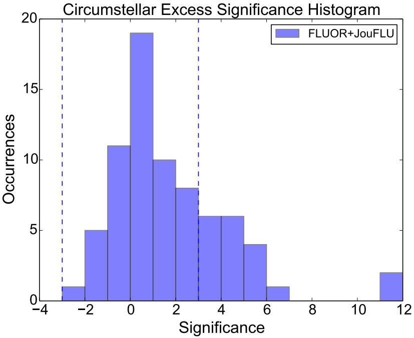




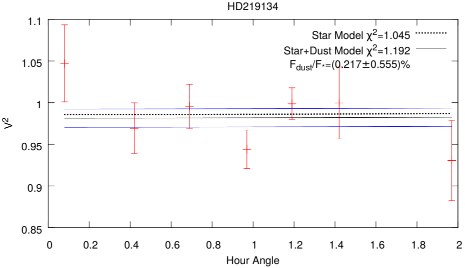
The median Kmag for the survey extension is ~ 1 higher than the initial survey, so errorbars should be larger by a factor of $\sim 1.5 - 2$.

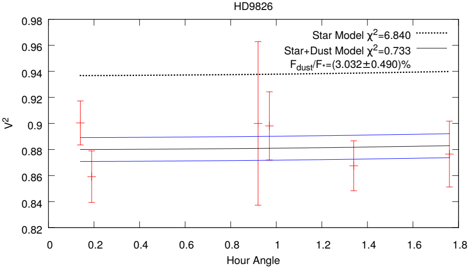
Significance Histograms





Examples from Recent Analysis (Preliminary)

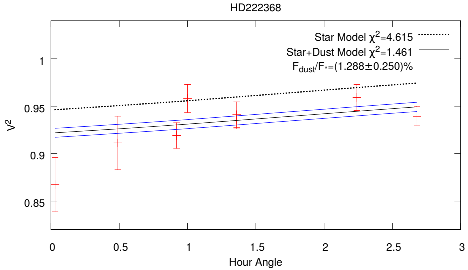


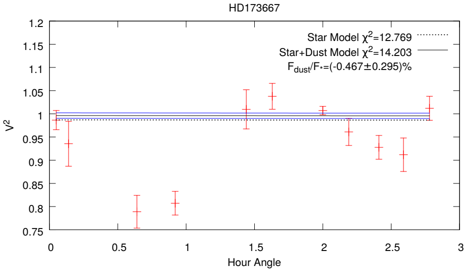


- Age: ~ 12 *Gyr*
- No detected NIR excess
- No detected FIR excess

- ups And
- Age: 6 *Gyr*
- $\sim 5\sigma$ NIR excess
- No detected FIR excess
- Exoplanet host star

Examples (Preliminary)





- iot Pcs
- Age: 3.9 *Gyr*
- $\sim 5\sigma$ NIR excess
- Detected FIR excess

- 110 Her (Absil excess)
- Age: 2.3 *Gyr*
- Binary likely
- Detected FIR excess

Summary of Results (Preliminary)

	A	F	G-K	Total
Outer reservoir	2/9	4/8	1/4	7/21
No outer reservoir	6/14	2/16	1/21	9/51
Total	8/23	6/24	2/25	16/72

NO statistically significant correlations yet, but...

- A (35%), F (25%), G-K (8%). $\sim 2\sigma$ result.
- Outer reservoir (33%), No outer reservoir (18%). $> 1\sigma$ diff

Conclusions and outlook

- Faint debris disks require very precise fringe visibility measurements ($\sim 1\%$)
- We have developed a data reduction pipeline which minimizes biases and errors (Nuñez et al. 2016, near submission)
- We have detected 7 new circumstellar excesses among the 37 stars analyzed (Nuñez et al. 2016, in preparation)
- Attributable to hot- and close-in dust in 5 cases. Binarity ruled out in most cases by RV studies
- Mechanism for dust replenishment/trapping is still subject of debate
- To do:
    - Lithium Niobate plates to maximize raw visibilities
    - Observations with S1-S2 equipped with adaptive optics