

Latest Results from the CHARA/JouFLU hot disks survey

Paul D. Nuñez

CHARA Science Meeting

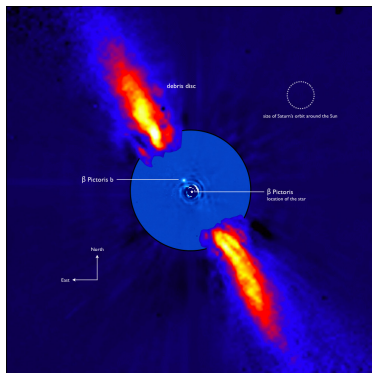
Current Team:

Bertrand Mennesson (JPL), Nic Scott (AMES), Theo ten Brummelaar (CHARA)

March 2017

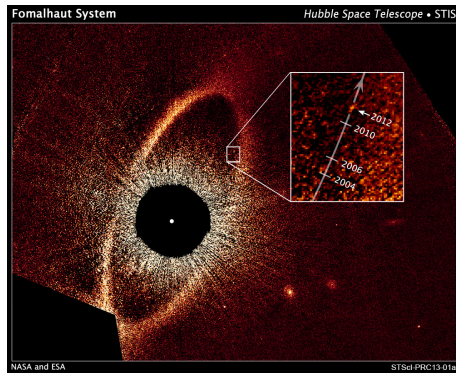
Towards direct imaging in the habitable zone

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



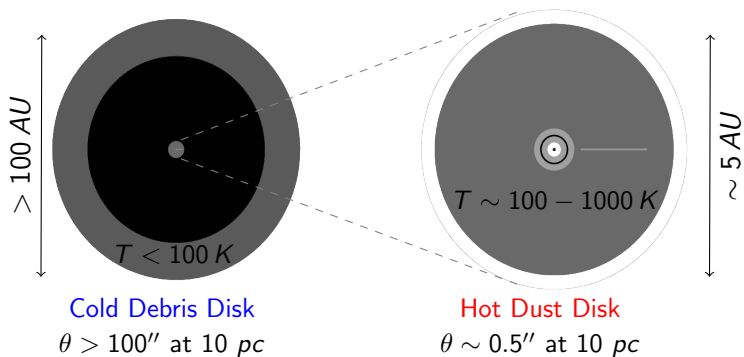
$D \approx 8 \text{ AU}$, $\theta_{\text{sep}} \approx 0.5''$
(Lagrange et al. 2009)

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



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

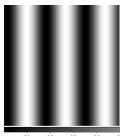
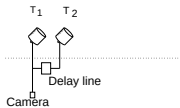
The Inner Hot Disk of Main Sequence Stars



- Must be understood to ensure success of future direct imaging missions
- Can be used to learn about planet formation

Resolving the Circumstellar environment

Distant star ●



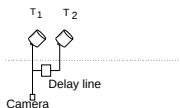
Unresolved Star

Resolving the Circumstellar environment

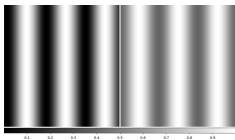
Distant star
+ Dust



The presence of a resolved circumstellar disk results in a loss of fringe contrast (visibility)



$$|V| = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \rightarrow \text{Fringe Visibility}$$

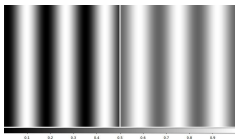
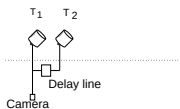


Unresolved Star | Star + Disk

Resolving the Circumstellar environment

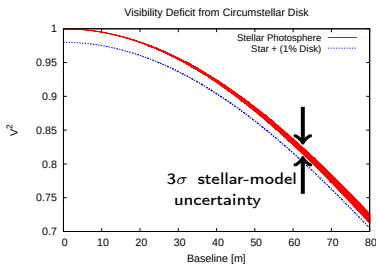
Distant star
+ Dust

The presence of a resolved circumstellar disk results in a loss of fringe contrast (visibility)



Unresolved Star | Star + Disk

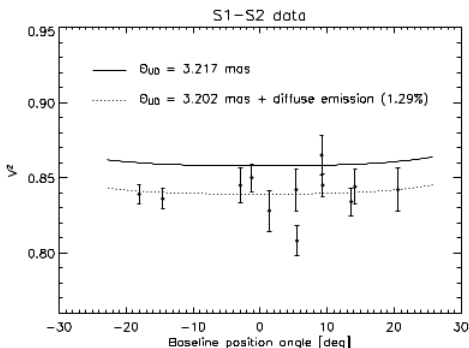
$$|V| = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \rightarrow \text{Fringe Visibility}$$



$$V_{(\star + disk)}^2 = |FT\{\star + disk\}|^2 \approx V_{\star}^2 (1 - 2f_{disk}/f_{\star})$$

NIR circumstellar excesses detected so far with CHARA

Inner disk of **Vega** resolved by CHARA (Absil et al. 2006)



- K band: $\lambda = (2.15 \pm 0.33) \mu\text{m}$
- $\sim 34 \text{ m}$ baseline and $0.5''$ FOV
 $\Rightarrow$ Emission from $0.1 - 7.8 \text{ AU}$
- Likely hot ($T \gtrsim 300 \text{ K}$) dust
- No dependence on phase angle
 $\Rightarrow$ uniform emission
- Results insensitive to photosphere model
- Previous MIR+FIR observations imply a cold debris disk as far as $\sim 200 \text{ AU}$ (Su et al. 2005)

NIR circumstellar excesses detected so far

+ 10 (out of 42) Main Sequence Stars (CHARA, Absil et al. 2013)

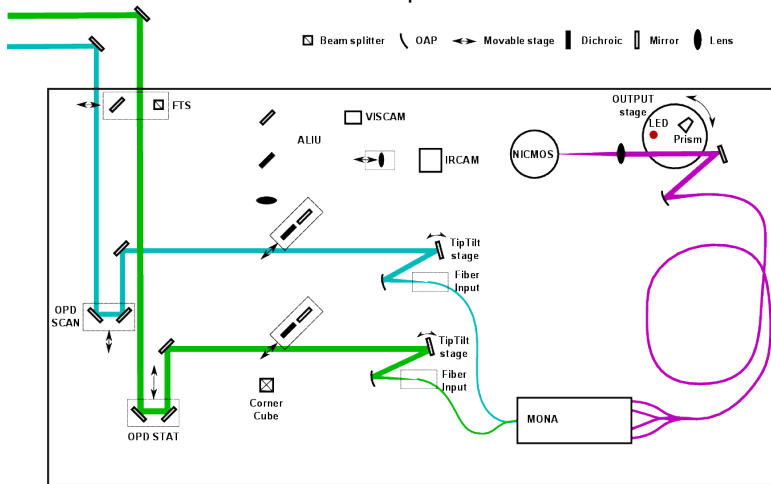
Name	$f_{\text{CSE}} (\%)$	$\sigma_f (\%)$	χ_r^2	χ_f	Excess?
bet Cas	0.07	0.30	0.90	0.2	NO
54 Psc	0.63	0.42	3.13	1.5	NO
eta Cas A	0.33	0.13	0.11	2.6	NO
ups And	0.53	0.17	2.62	3.0	NO ^c
107 Psc	0.75	0.57	2.07	1.3	NO
tau Cet ^a	0.98	0.18	0.83	5.4	YES
tet Per	0.44	0.27	1.82	1.6	NO
eps Eri ^a	-0.10	0.20	2.44	-0.5	NO
10 Tau	1.21	0.11	1.76	11.0	YES
1 Ori	0.44	0.23	2.92	1.9	NO
zet Lep	0.55	0.26	1.33	2.1	NO
eta Lep	0.89	0.21	2.20	4.3	YES
ksi Gem	-1.36	0.69	1.41	-2.0	NO
lam Gem	0.74	0.17	2.35	4.3	YES
HD 69830	-0.23	0.45	0.13	-0.5	NO
30 Mon	0.04	0.45	0.69	0.1	NO
bet UMa ^b	-0.05	0.16	0.40	-0.3	NO
del Leo	-1.14	0.77	0.53	-1.5	NO
bet Leo	0.94	0.26	5.50	3.6	YES
bet Vir	0.06	0.33	1.84	0.2	NO

Name	$f_{\text{CSE}} (\%)$	$\sigma_f (\%)$	χ_r^2	χ_f	Excess?
70 Vir	0.12	0.27	0.59	0.5	NO
iot Vir	-0.75	0.25	1.20	-3.0	NO
sig Boo ^b	0.40	0.45	1.80	0.9	NO
ksi Boo	0.74	0.20	0.21	3.7	YES
lam Ser	0.55	0.35	2.25	1.6	NO
kap CrB	1.18	0.20	1.16	5.9	YES
chi Her	0.58	0.65	1.58	0.9	NO
gam Ser	-0.06	0.27	0.11	-0.2	NO
mu Her	1.02	0.33	2.58	3.1	NO ^c
gam Oph ^b	0.25	0.48	1.23	0.5	NO
70 Oph A	0.31	0.36	2.40	0.9	NO
alf Lyr ^b	1.26	0.27	2.11	4.7	YES
110 Her	0.94	0.25	0.35	3.8	YES
zet Aql ^b	1.69	0.27	0.97	6.3	YES
sig Dra	0.15	0.17	1.55	0.9	NO
alf Aql	3.07	0.24	1.75	12.9	YES
61 Cyg A	0.13	0.55	0.49	0.2	NO
61 Cyg B	-0.36	0.36	0.94	-1.0	NO
alf Cep	0.87	0.18	1.79	4.7	YES
eps Cep	3.25	0.69	13.77	4.7	YES

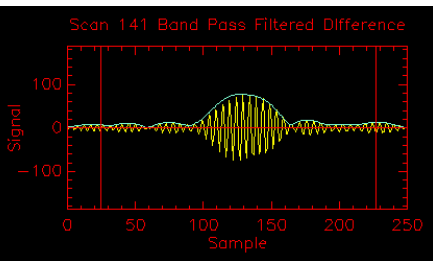
+ 4 in H band ($1.6 \mu\text{m}$) with VLT/PIONIER (Ertel et al. 2014)

CHARA/JouFLU (K band)

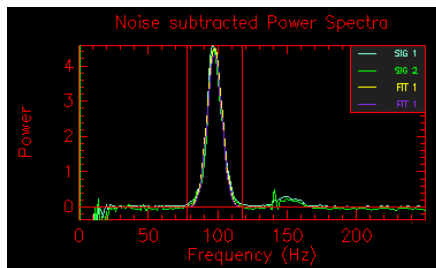
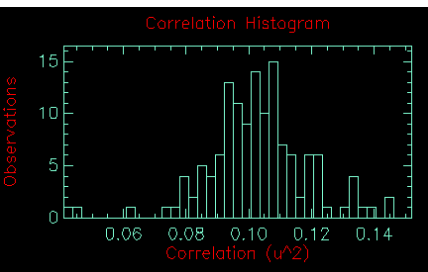
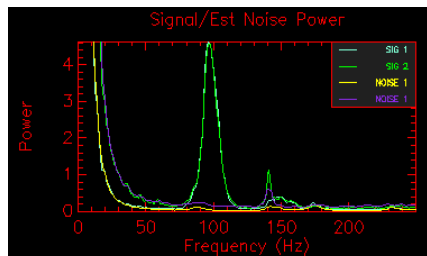
Fiber-Linked Unit for Optical Recombination



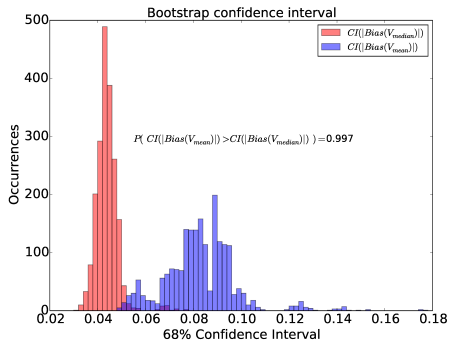
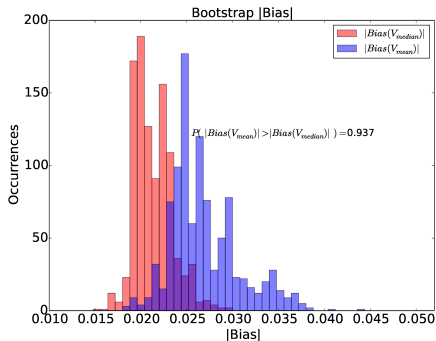
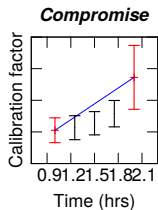
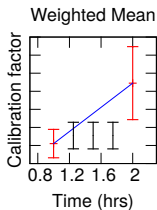
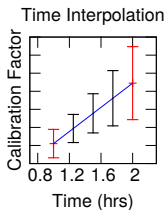
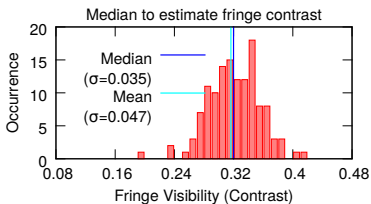
Example Data for Altair... with improved pipeline



FT
→

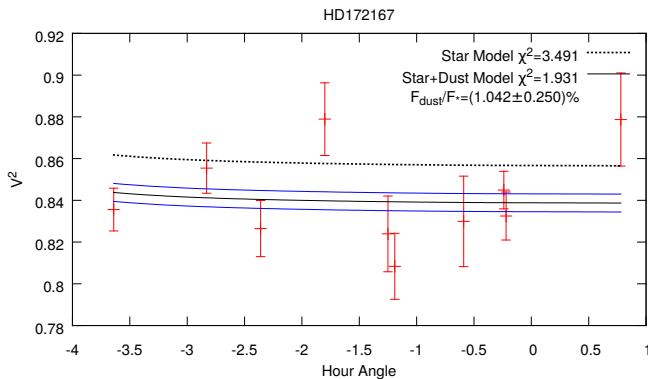


Data Reduction: Nuñez, ten Brummelaar, Mennesson, Scott. PASP, 2017



Checking new pipeline on old (2005) FLUOR data

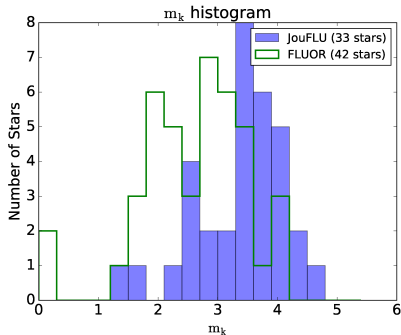
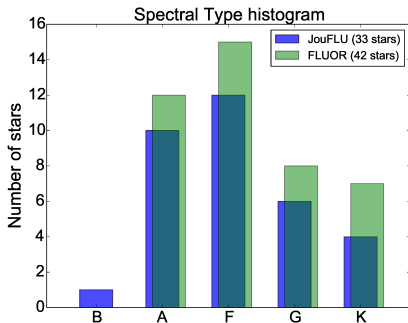
Excess level of Vega using new pipeline is consistent with Absil et al. (2006)



To compare with $f_{\text{cse}} = (1.26 \pm 0.27)\%$

K-Band Observations after 2012

33 new stars, 11 follow-ups of previous survey

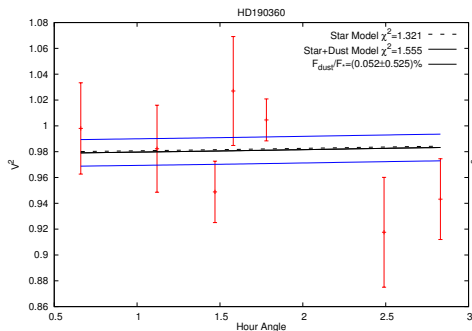


- Total of 75 stars: 21 with a known outer cold reservoir.
- Nominally 3 calibrators per target.
[cal₁-sci-cal₂-sci-cal₃-sci-cal₁] $\times 2$
- Goal: to search for correlations of hot dust with spectral type, age, cold-dust...

Survey Results: 33 stars, 6 new excesses, 4 due to binarity

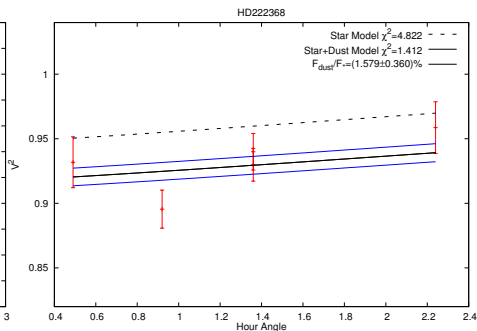
HD	Name	Type	K	Baseline	$f_{\text{cse}}(\%)$	χ^2_{cse}	χ^2_*
5015	HR 244	F9V	3.54	S1-S2	0.61 ± 0.83	1.79	1.68
5448	37 And	A5V	3.5	S1-S2	2.64 ± 0.53	0.716	5.24
6961	θ Cas	A7V	3.97	S1-S2	0.64 ± 0.67	3.4	2.91
10780	V987 Cas	K0V	3.84	S1-S2	2.34 ± 0.89	3.42	3.47
14055	γ Tri	A1Vnn	3.96	E1-E2	-1.39 ± 1.08	0.891	1.67
15335	13 Tri	G0V	4.48	E1-E2	0.60 ± 1.41	0.651	0.51
19373	ι Per	F9.5V	2.68	S1-S2	-0.36 ± 0.28	2.267	2.12
20630	κ 1 Cet	G5Vv	3.34	E1-E2	1.39 ± 1.03	0.83	1.08
23249	δ Eri	K1III-IV	1.43	E1-E2	1.40 ± 0.77	0.092	1.75
26965	40 Eri	K0.5V	2.498	S1-S2	0.01 ± 0.76	1.94	1.39
28355	79 Tau	A7V	4.55	E1-E2	-0.86 ± 1.23	4.157	3.16
33111	β Eri	A3IV	2.38	S1-S2	3.21 ± 0.37	6.35	17.67
34411	λ Aur	G1.5IV-V	3.27	E1-E2	0.25 ± 0.56	0.525	0.48
50635	38 Gem	F0Vp	3.89	E1-E2	2.0 ± 1.0	3.93	3.55
87901	α Leo	B8IVn	1.60	S1-S2	-0.12 ± 0.79	0.539	0.37
162003A	HR 6636	F5IV-V	3.43	E1-E2	7.44 ± 0.52	1.431	29.02
164259	ζ Ser	F2IV	3.67	E1-E2	0.76 ± 0.88	2.748	2.48
165777	72 Oph	A4IVs	3.42	E1-E2	3.27 ± 1.46	1.46	1.68
168151	LTT 15404	F5V	3.85	E1-E2	1.84 ± 0.76	3.30	3.89
182572	31 Aql	G8IV	3.53	E1-E2	0.03 ± 0.6	2.34	2.05
182640	δ Aql	F0IV	2.52	S1-S2	7.2 ± 0.41	1.91	51.24
184006	ι Cyg	A5V	3.598	E1-E2	-0.54 ± 0.875	1.581	1.32
187691	LTT 15798	F8V	3.902	E1-E2	1.17 ± 1.87	0.48	0.84
190360	LHS 3510	G7IV-V	4.05	E1-E2	0.05 ± 0.52	1.55	1.32
192640	V1644 Cyg	A2V	4.47	E1-E2	2.16 ± 1.35	1.667	1.95
202444	τ Cyg	F0IV	2.69	S1-S2	2.83 ± 1.35	3.44	3.58
210418	θ Peg	A1Va	3.33	E1-E2	1.69 ± 0.54	1.67	2.80
213558	α Lac	A1V	3.75	E1-E2	-1.17 ± 0.86	0.43	0.71
215648	LHS 3851	F7V	2.92	S1-S2	0.51 ± 0.42	1.08	1.17
217014	51 Peg	G2.5IVa	3.99	E1-E2	-0.03 ± 0.76	0.62	0.51
219080	7 And	F0V	3.77	S1-S2	-0.2 ± 0.54	0.98	0.87
219134	HR 8832	K3V	3.12	S1-S2	0.58 ± 0.54	1.61	1.55
222368	ι Psc	F7V	2.82	E1-E2	1.58 ± 0.36	1.41	4.82

Example detection and non-detection



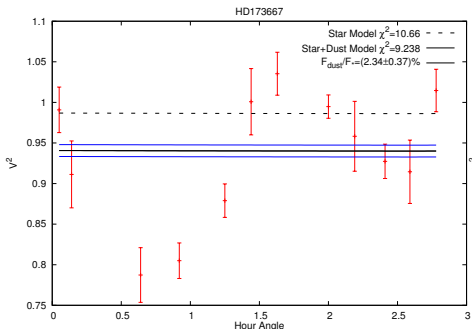
- Age: ~ 12.1 Gyr
- Exoplanet host star
- No detected NIR excess

(Nuñez et al. 2017, soon!)



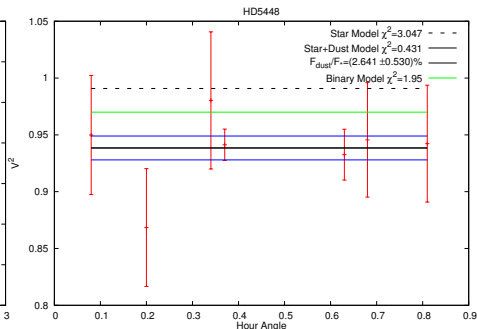
- ι Psc
- Age: 5.2 Gyr
- $\sim 4.4\sigma$ K-band excess
- Detected FIR excess ($70\ \mu\text{m}$)
(Trilling et al. 2008)
- No excess at $10\ \mu\text{m}$ with KIN
(Mennesson et al. 2014)

Binaries or Dust?



- 110 Her
- Excess candidate by Absil et al. 2013

(Nuñez et al. 2017, soon!)



- 37 And
- Faint companion discovered recently (Roettenbacher et al. 2016)

Results of follow-up observations

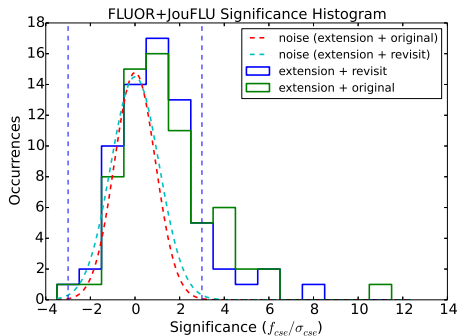
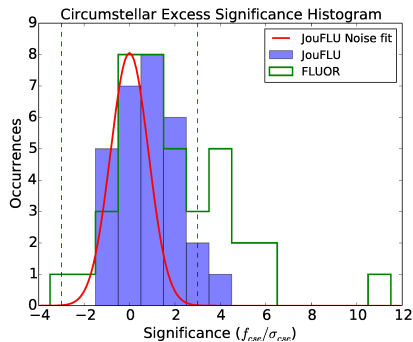
Table : circumstellar emission for the follow-up targets of Absil (2013).
The highlighted boxes correspond to statistically significant excesses: red boxes indicate that the excess is statistically significant, and also consistent with the circumstellar dust model.

HD	Name	Type	K	Baseline	$f_{\text{cse}}(\%)$ JouFLU	χ^2_{cse}	χ^2_*	$f_{\text{cse}}(\%)$ FLUOR	$\Delta f_{\text{cse}}(\%)$
9826	v And	F9V	2.84	S1-S2	3.62 ± 0.61	1.26	4.42	0.53 ± 0.17	3.09 ± 0.63
40136	η Lep	F2V	2.91	S1-S2	0.45 ± 0.47	2.03	1.8	0.89 ± 0.21	0.44 ± 0.52
102647	β Leo	A3Va	1.91	S1-S2	1.09 ± 0.52	0.90	1.44	0.94 ± 0.26	0.15 ± 0.59
131156	ξ boo	G7V	1.97	S1-S2	-0.32 ± 0.42	1.40	1.29	0.74 ± 0.20	-1.06 ± 0.47
142091	κ CrB	K1IV	2.49	S1-S2, E1-E2	3.4 ± 0.52	1.85	6.54	1.18 ± 0.20	2.22 ± 0.56
142860	γ Ser	F6IV	2.62	E1-E2	1.09 ± 0.78	1.02	1.17	-0.06 ± 0.27	1.15 ± 0.94
173667	110 Her	F6V	3.05	S1-S2	2.34 ± 0.37	10.66	9.24	0.94 ± 0.25	1.40 ± 0.44
177724	ζ Aql	A0Vn	2.9	E1-E2	1.23 ± 0.38	1.32	2.45	1.69 ± 0.27	-0.46 ± 0.47
185144	σ Dra	G9V	2.81	S1-S2	-1.11 ± 1.0	1.88	1.78	0.15 ± 0.17	-1.26 ± 1.01
187642	α Aql	A7V	0.22	S1-S2	6.11 ± 0.74	2.76	27.33	3.07 ± 0.24	3.05 ± 0.78
203280	α Cep	A7IV	1.96	E1-E2	-0.14 ± 0.78	0.74	0.64	0.87 ± 0.18	-1.01 ± 0.8

4 excess levels changed significantly, 1 likely due to binarity.

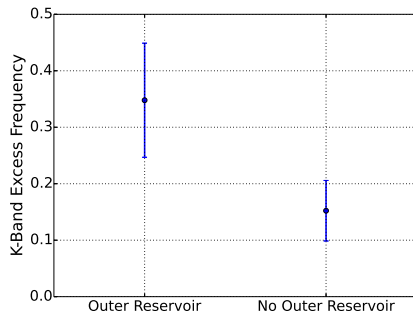
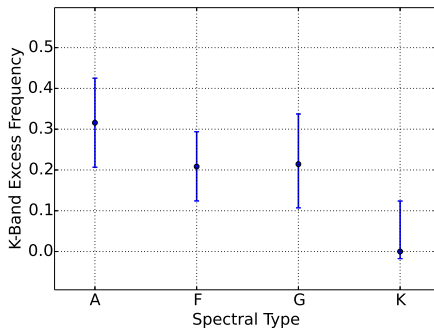
Summary of Results

6 new stars with a visibility deficit, 2 stars with dust, 4 binaries.



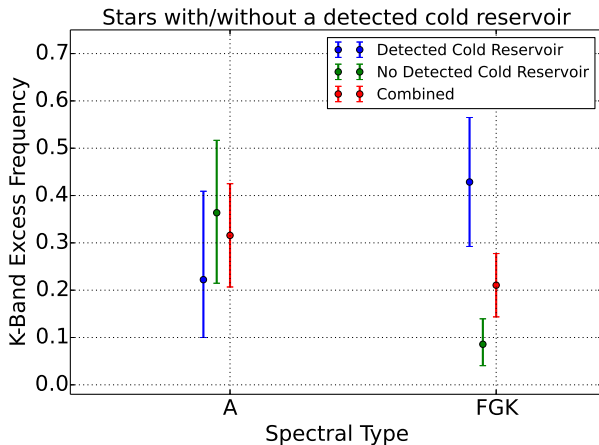
- Weighted mean of circumstellar emission is $(0.36 \pm 0.12)\%$
- Instrumental noise significance distribution has $\text{std} \approx 1$

Correlations with Spectral Type and Cold Dust?



- No significant correlation with spectral type or cold dust. But...

FGK detections seem to correlate with cold dust



Different excess mechanism for the A-type excesses?

Location of the Dust

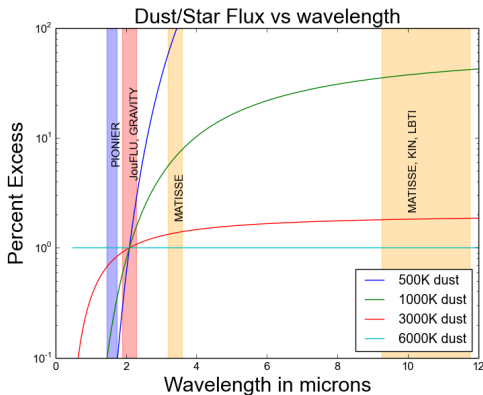


Fig: Assuming thermally emitting dust, with a K-band flux ratio of 1% relative to a star of 6000 K, the curves show the expected contrast as a function of wavelength

⇒ Inner dust likely to be composed of close-in, hot ($T \sim 1000\text{ K}$) and small $\sim 1\mu\text{m}$ grains close to sublimation radius at $\sim 0.1\text{ AU}$

- No corresponding excesses at $\sim 10\mu\text{m}$ (Mennesson+ 2014)
- Less detections in H band vs K band (Ertel+ 2014). (Different samples).
- Marshall+ (2016) finds no scattered light on excess stars via polarimetry
- Modeling is consistent with micron-sized hot dust (Kirchschlager+ 2017)

Some implications/issues raised by observations

- **How does the dust get there? And how is it replenished?**

Small- and close-in dust should have a very short lifetime

($\sim$ years)

A few replenishment possibilities: comet in-fall/out-gassing (Wyatt 2008; Su+ 2013; Lebreton+ 2013). Magnetic trapping of nano-grains (Rieke+. 2016)

Much of our zodiacal dust is thought to originate from comets



Summary and final remarks

- Developed an optimized data reduction pipeline, which minimized the visibility bias and uncertainty
- Tested pipeline on old data FLUOR data. We reproduce excess levels and uncertainties
- Added 33 new stars to the sample. 6 new stars with significant circumstellar emission. 4 binaries, 2 attributed to dust
- Testing with binaries: measured visibility deficits are compatible with expected values
- 69 stars when combining FLUOR and JouFLU
- Detection rate of $(21.7 \pm 5.0)\%$
- Excesses are more frequent in FGK Stars with detected cold debris disk than without a detected cold debris disk
- 2 Exoplanet host stars display and excess: υ And, κ CrB, significantly higher than before.