First Science with JouFLU

long-baseline optical interferometry and exo-zodiacal dust

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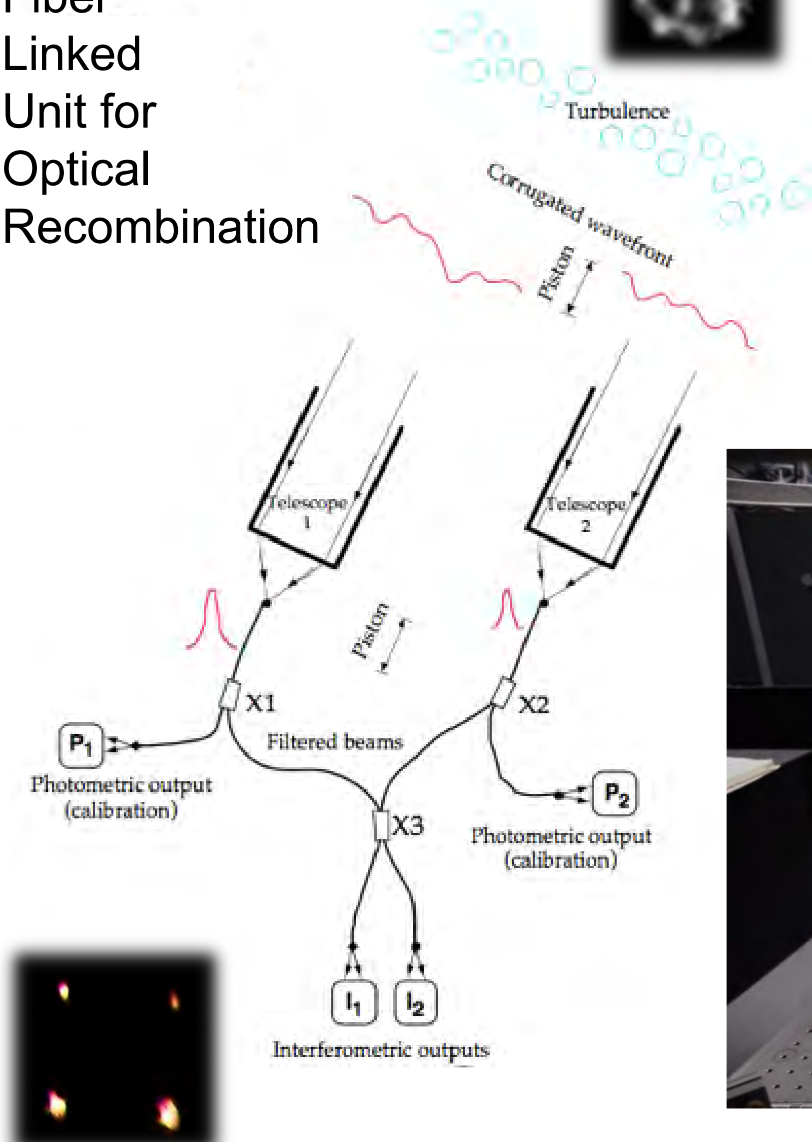
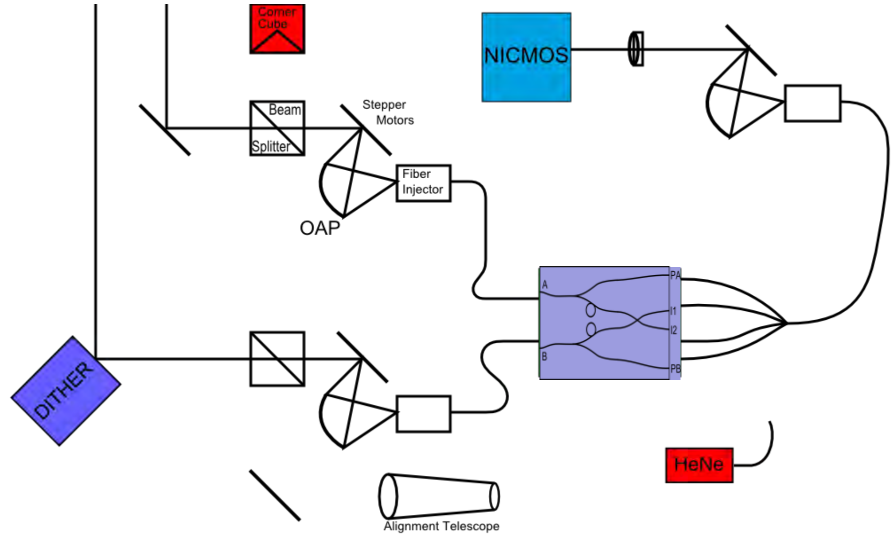
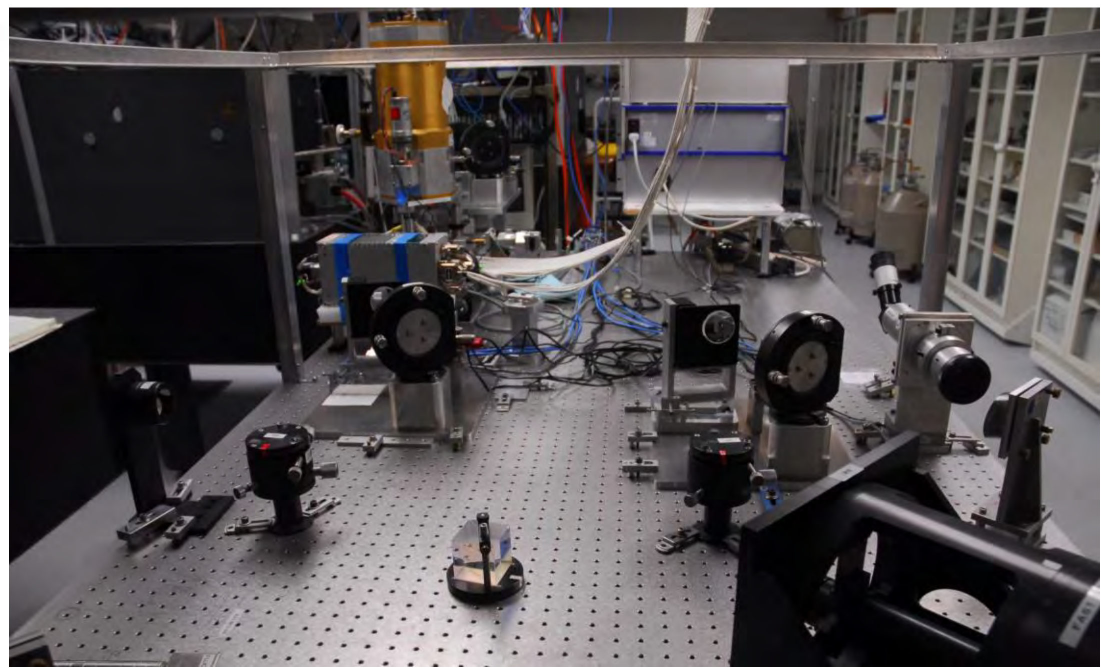
Georgia State University

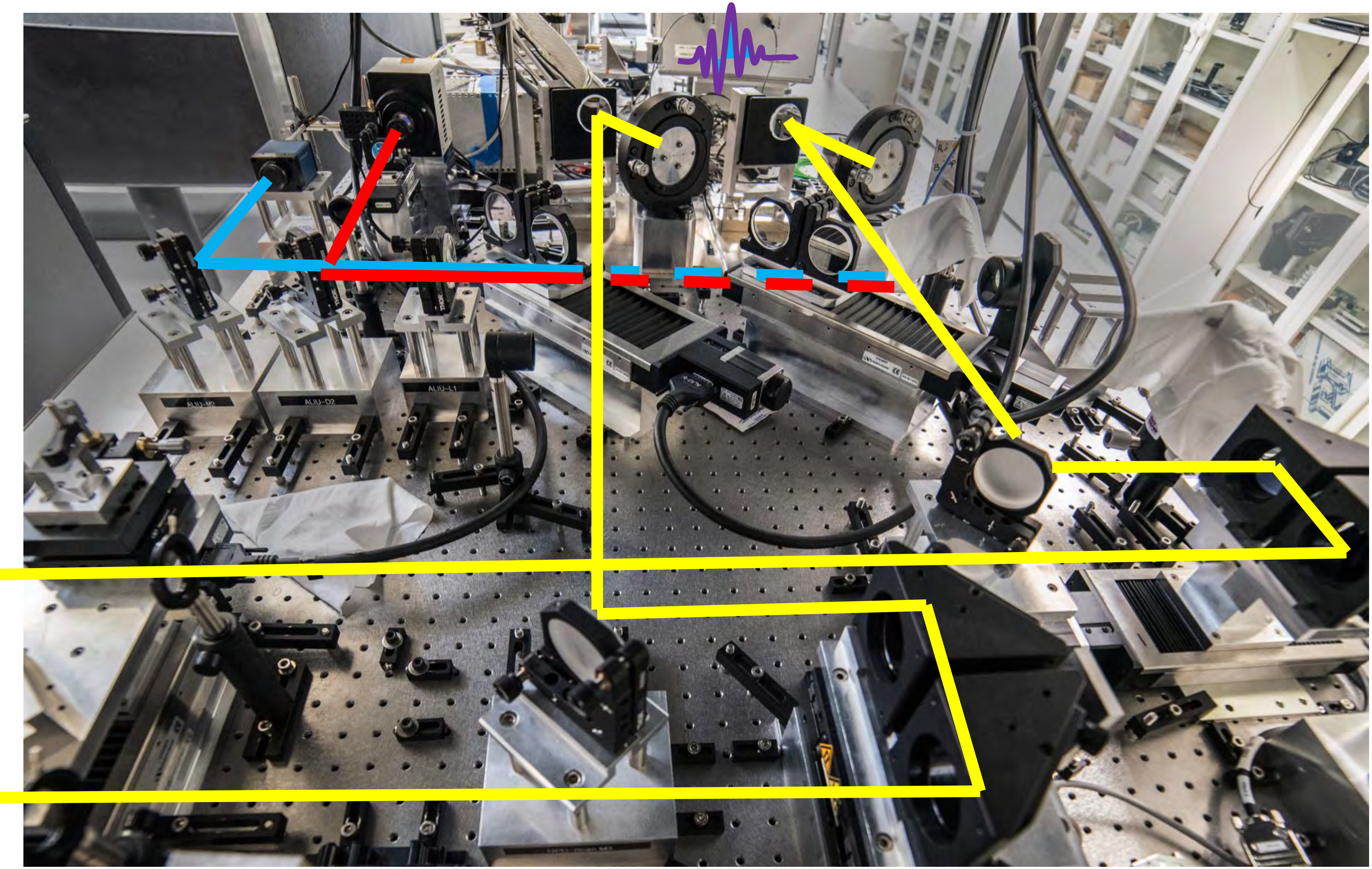
CHARA

Fiber Linked Unit for Optical Recombination

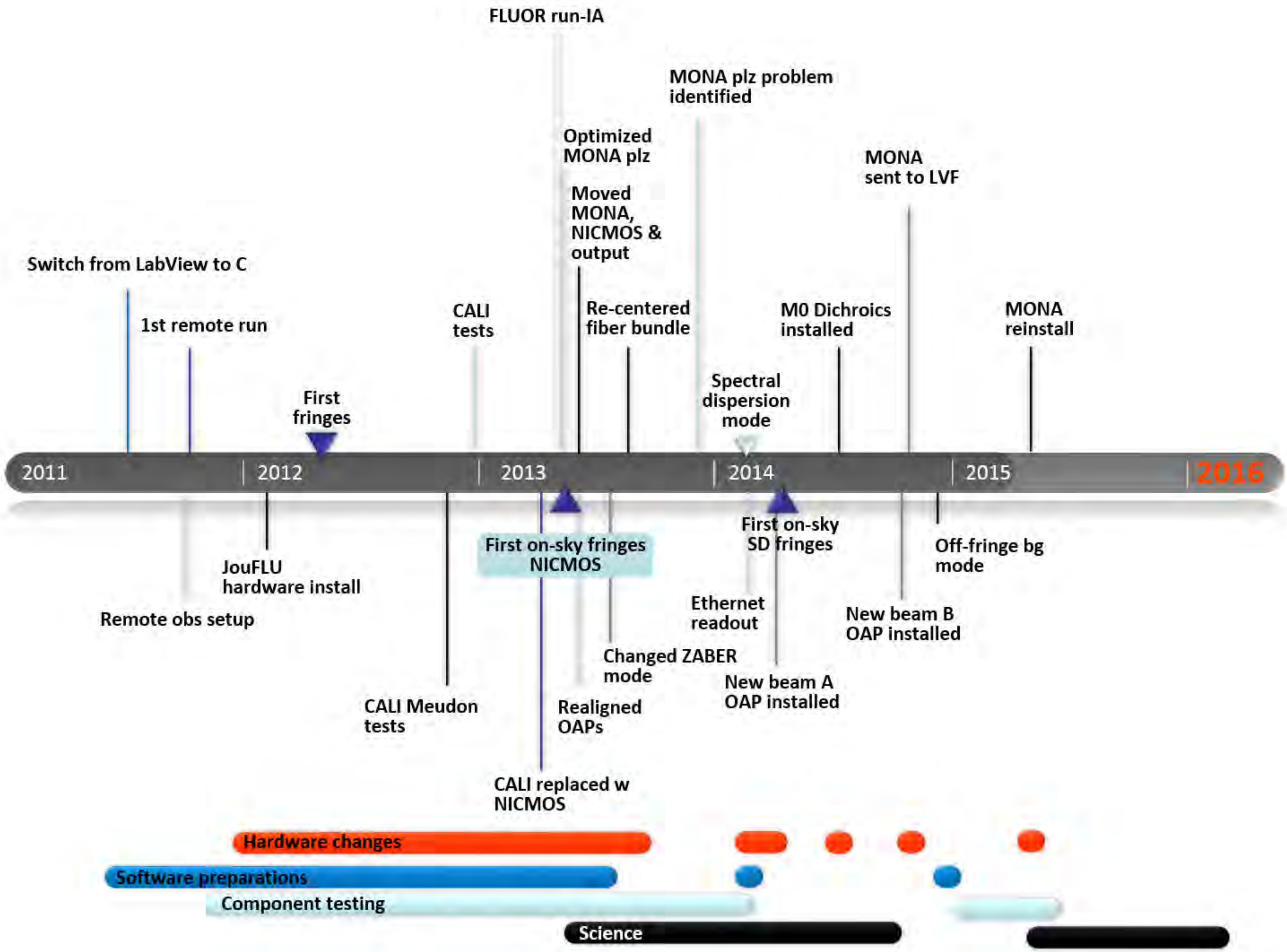


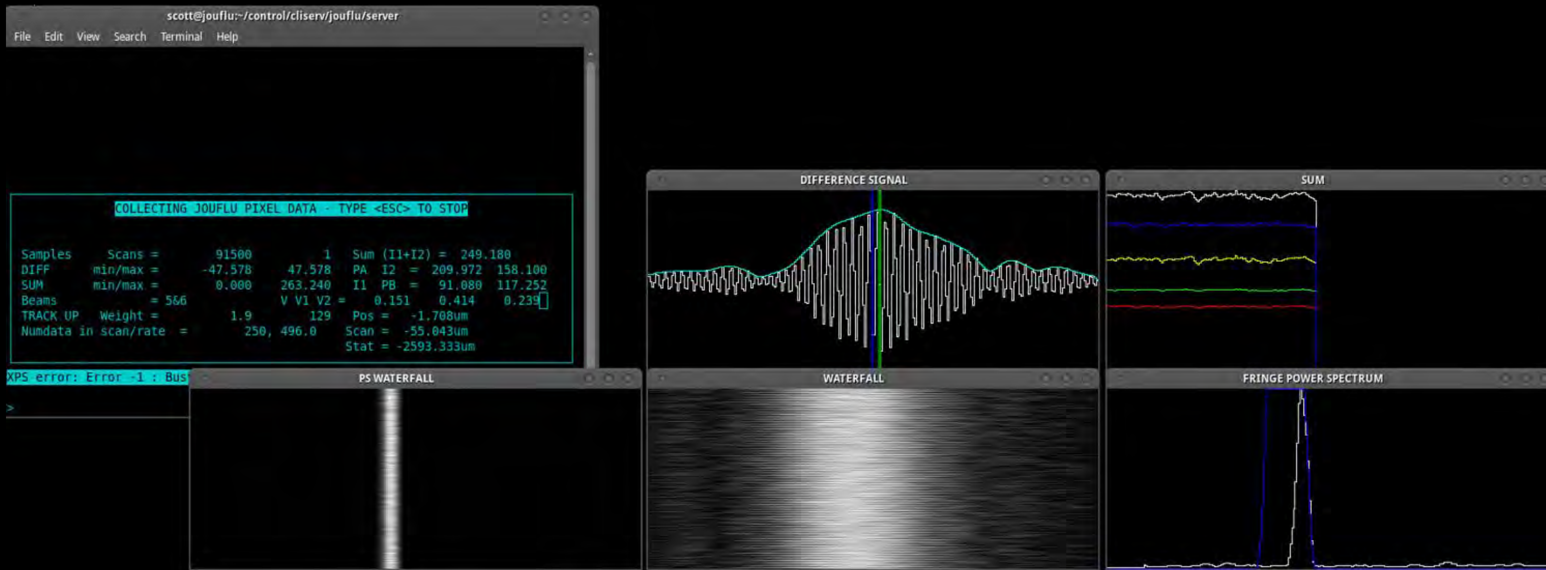


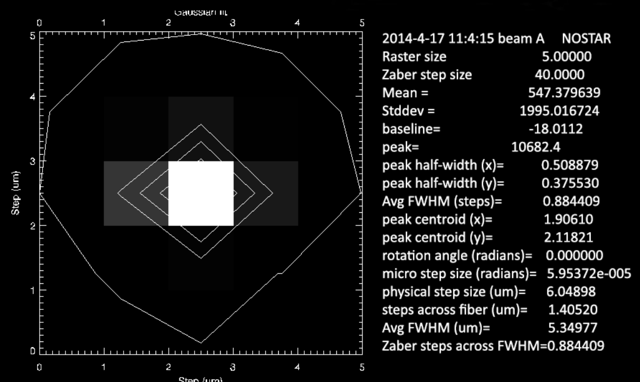




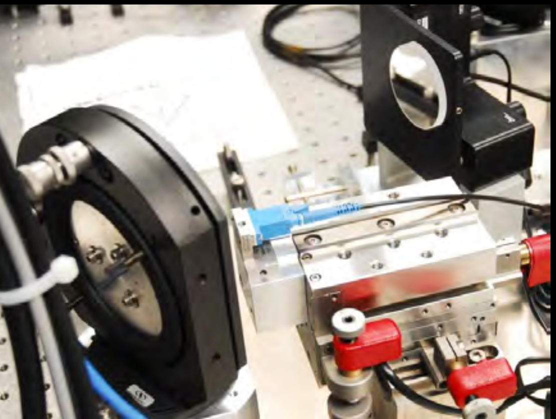
ALIU-M2
ALIU-D2
ALIU-L1


FLUOR run-IA
MONA plz problem identified
Optimized MONA plz
Moved MONA, NICMOS & output
MONA sent to LVF
Switch from LabView to C
1st remote run
CALI tests
Re-centered fiber bundle
M0 Dichroics installed
MONA reinstall
Spectral dispersion mode
First fringes
2011
2012
2013
2014
2015
2016
First on-sky fringes NICMOS
First on-sky SD fringes
Off-fringe bg mode
JouFLU hardware install
Remote obs setup
Ethernet readout
New beam B OAP installed
Changed ZABER mode
New beam A OAP installed
CALI Meudon tests
Realigned OAPs
CALI replaced w NICMOS
Hardware changes
Software preparations
Component testing
Science


scott@jouflu:~/control/cliserv/jouflu/server
File Edit View Search Terminal Help
COLLECTING JOUFLU PIXEL DATA - TYPE <ESC> TO STOP
Samples Scans = 91500 1 Sum (I1+I2) = 249.180
DIFF min/max = -47.578 47.578 PA I2 = 209.972 158.100
SUM min/max = 0.000 263.240 I1 PB = 91.080 117.252
Beams = 566 V V1 V2 = 0.151 0.414 0.239
TRACK UP Weight = 1.9 129 Pos = -1.708um
Numdata in scan/rate = 250, 496.0 Scan = -55.043um
Stat = -2593.333um
XPS error: Error -1 : Bus
DIFFERENCE SIGNAL
SUM
PS WATERFALL
WATERFALL
FRINGE POWER SPECTRUM

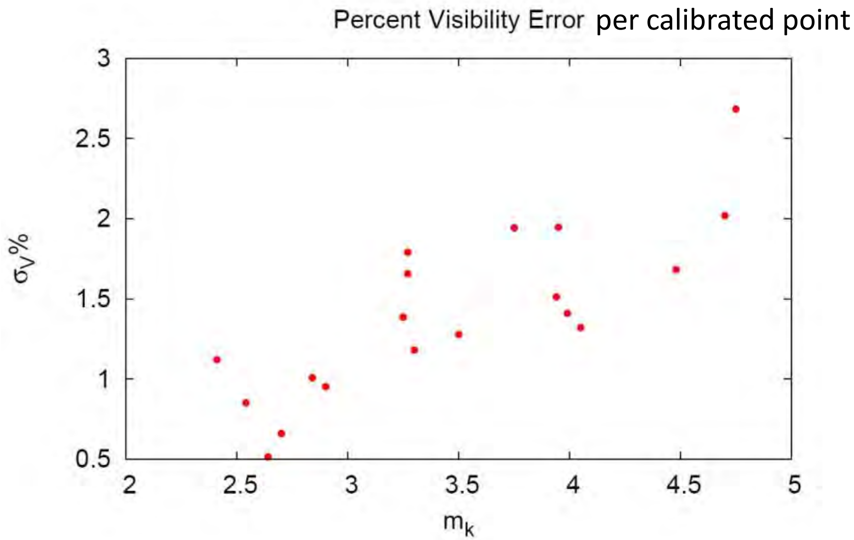

Gaussian fit
Step (um)
Step (um)
2014-4-17 11:4:15 beam A NOSTAR
Raster size 5.00000
Zaber step size 40.0000
Mean = 547.379639
Stddev = 1995.016724
baseline= -18.0112
peak= 10682.4
peak half-width (x)= 0.508879
peak half-width (y)= 0.375530
Avg FWHM (steps)= 0.884409
peak centroid (x)= 1.90610
peak centroid (y)= 2.11821
rotation angle (radians)= 0.000000
micro step size (radians)= 5.95372e-005
physical step size (um)= 6.04898
steps across fiber (um)= 1.40520
Avg FWHM (um)= 5.34977
Zaber steps across FWHM=0.884409


JOUFLU
MAIN SETUP NICMOS XPS IRCAM ALIGN PICTURE PHOTOM DATA STATUS CONFIGURE
LAB Dith (um) 110 NICMOS lngth 250 Save SkipLow Memory START
Not saving data Scans 0 SERVO OFF
I1 Mag Lim 4.9 I2 Mag Lim 5.5 P1 Mag Lim 5.8 P2 Mag Lim 5.2
V 0.151 V1 0.414 V2 0.239 SNR 1.9e+00 Targ 0.0um Pos -1.7um Cart -2593.3um Sum 249.2
< > << >> <<< >>> <<<< >>>> S< S>
HOLD SEND CLEAR FILT DIFF/SIG AUTO UP DN PSN
SERVO SAVE T+5 T-5 FRGTRCK WATERFLL AUTOMODE STOP ABORT
REOPEN NICMOS PING REOPEN CLEAR DISP QUIT




JOUFLU PICTURE

JouFLU mag limit

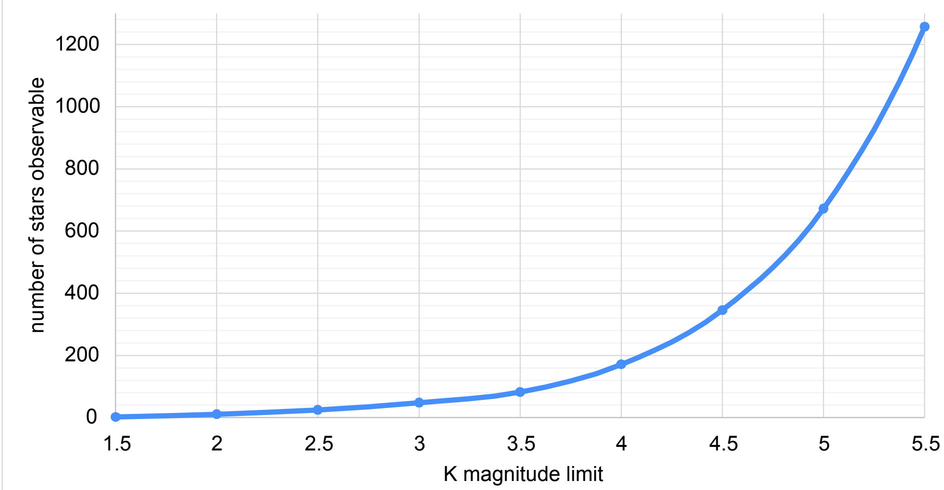


$$m_{\mathrm{k,lim}} = -2.5 \log \frac{\mathrm{F}_\nu}{f_\nu}$$

$$\mathrm{F}_\nu = \frac{\mathrm{n_{incident}} \cdot \mathrm{R} \cdot \mathrm{h}}{10^{-26} \cdot \mathrm{t_{int}}}$$

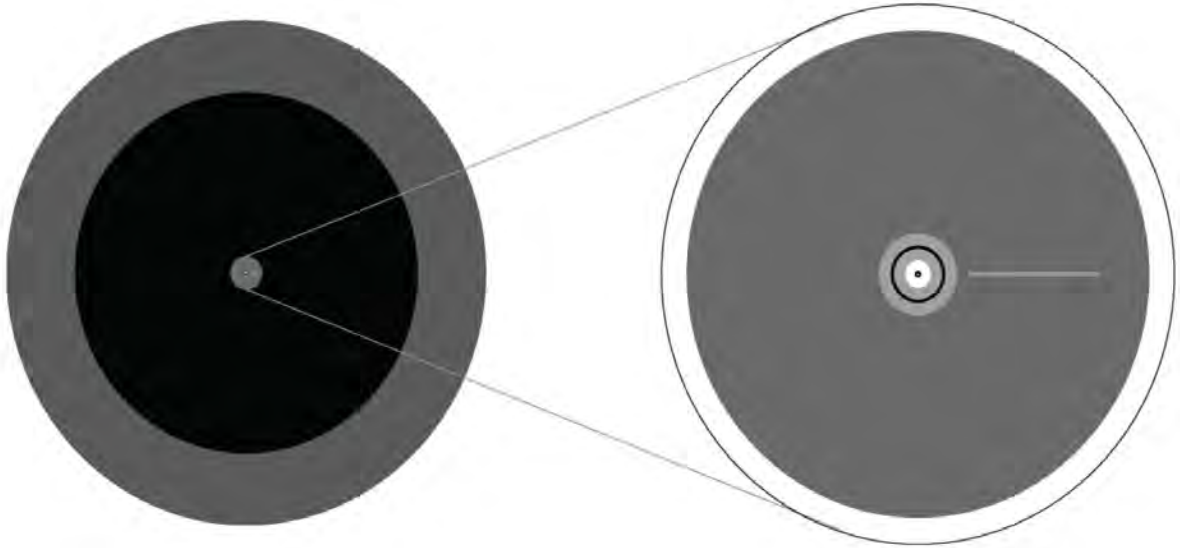
$$n_{\mathrm{incident}} = \frac{n_{\mathrm{counts}} \cdot \mathrm{gain} \cdot \mathrm{A_{tel}}}{\mathrm{eff}}$$

$$m_{\mathrm{k,lim}} = -2.5 \log \frac{n_{\mathrm{counts}} \cdot \mathrm{gain} \cdot \mathrm{A_{tel}} \cdot \mathrm{R} \cdot \mathrm{h}}{\mathrm{eff} \cdot 10^{-26} \cdot \mathrm{t_{int}} \cdot \mathrm{f}_\nu}$$



$\mathrm{K_{mag}} = 4.54$ (science)….
fringes possible on 5.2 (but VERY difficult)

This should improve by ~1 mag with lithium niobate!
….soon AO will help as well!



	Conventional detection level [Spitzer, Herschel]
>100 AU	cold debris disk (<100K)
10 AU	giant planet
<10 AU	exozodiacal dust (100-1400K)

	Interferometric field-of-view
<10 AU	exozodiacal dust (100-1400K)
2 - 7 AU	habitable zone (line)
1 AU	terrestrial planet with gap
0.5 - 1.5 AU	warm dust disk (500K)
0.1 - 0.5 AU	hot dust disk (>1000K)
center	A0 star

Debris disks – left over from planetary formation, late heavy bombardment period (LHB)

- 20% of MS systems are thought to harbor DD (Trilling et al. 2008, Carpenter et al. 2009, Eiroa et al. 2013)
- Space missions: IRAS, HST, ISO, Spitzer, Herschel
- Far-IR excess, Sub-mm imaging, Visible imaging

Exozodiacal analogs

- Tenuous but huge in surface area
- Grains < 1-100 μm in diameter
- Debris from comets, asteroids, collisions and outgassing

NIR results → large populations of hot small grains close in to nearby MS stars

- Possibly Mg-rich forsterite (peridot, Mg_2SiO_4) (Lisse 2015, Su 2015)
- Sub-micron grains should be short lived in this region (Wyatt 2008)

Trapped or replenished by catastrophes – different timescale for each mechanism

Highly variable on short time-scales due to short orbital period

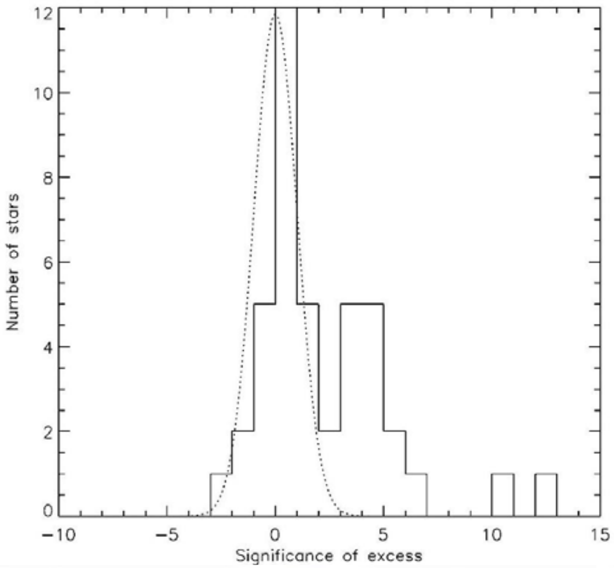
- Meng et al. (2014) reports quasi-periodic (P≈70 days) disk flux modulation in MIR spectra
- Giant impact resulted in a thick cloud of silicate spherules that were then ground into dust 'panel' by collisions
- Mass loss rate ≈ 180 km diameter asteroid every < 10 yrs,
- Not uncommon, 4 other similar systems

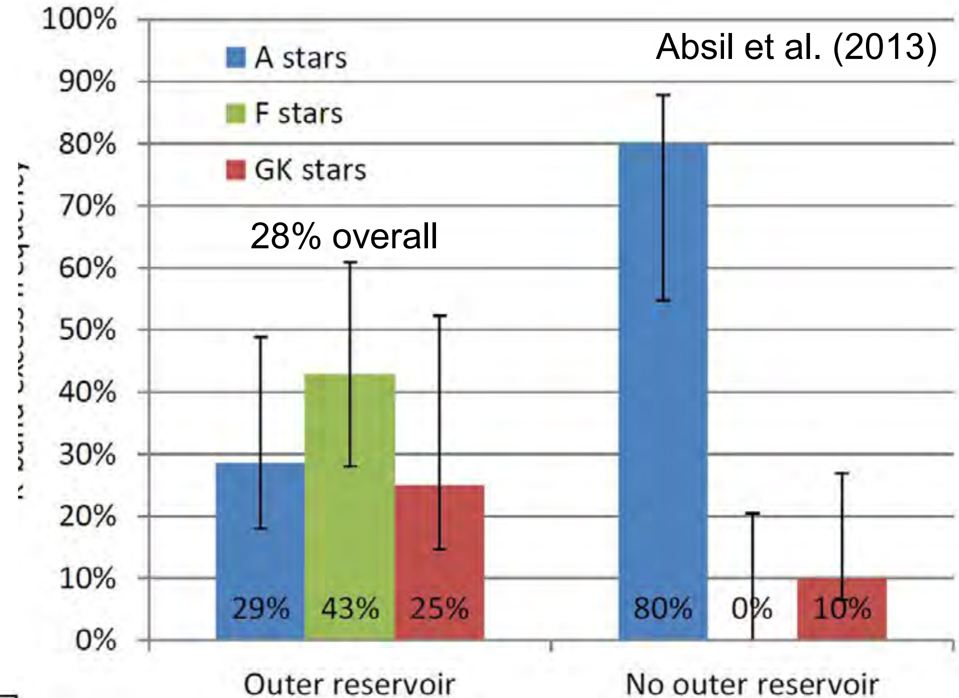
Other explanations?

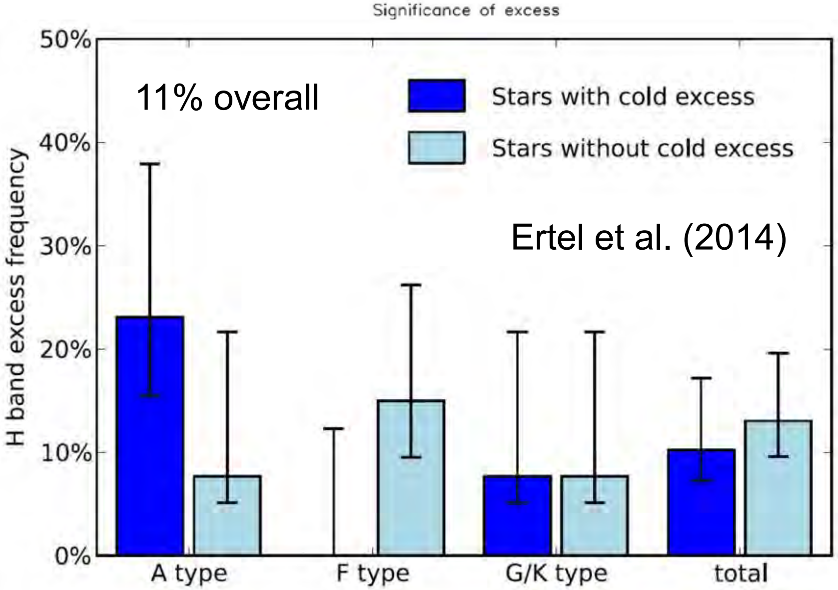
Could excess not be due to dust/disk?

- Point sources I: RV & astrometry stable
- Point sources II: companion of 350 to 1000 mas separation cannot be ruled out (Absil et al. 2006)
  - PFN limits excess to either very close or far from star
  - Follow up with Speckle
- Point sources III: field star ruled out by other IR surveys (2MASS, etc), 1:500,000 chance
- Stellar Winds:
  - weak for A stars

First statistics based on 42 stars observed with CHARA/FLUOR



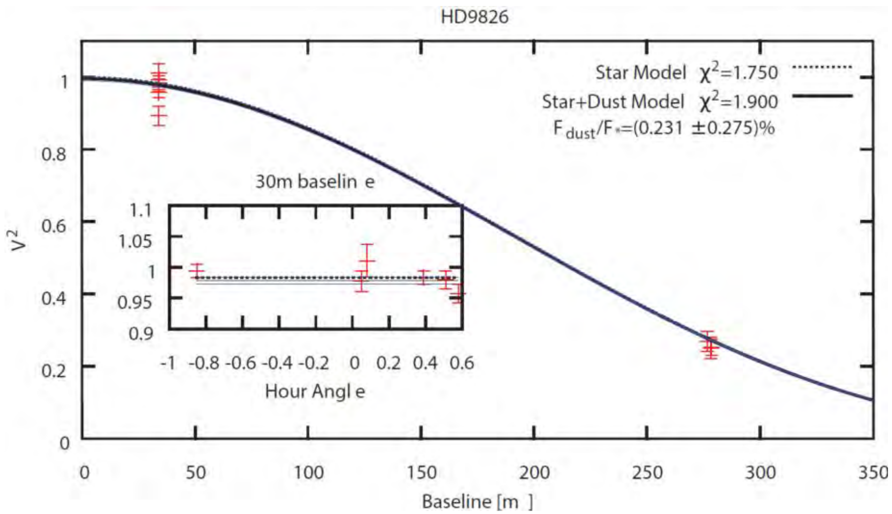


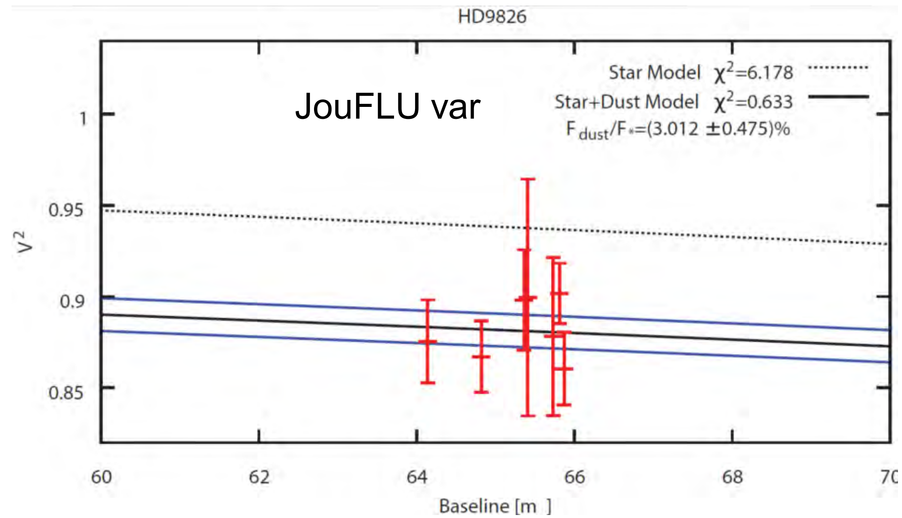


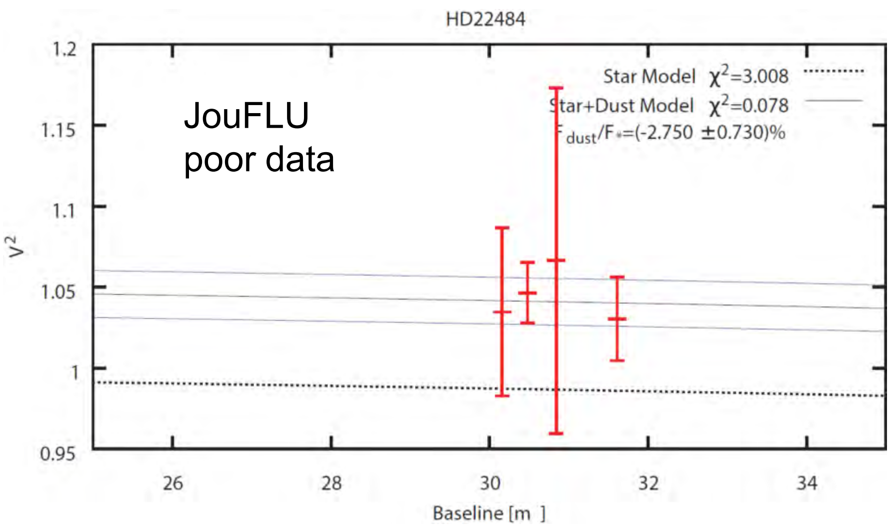
28% of nearby MS A-K type stars show NIR interferometric exozodis

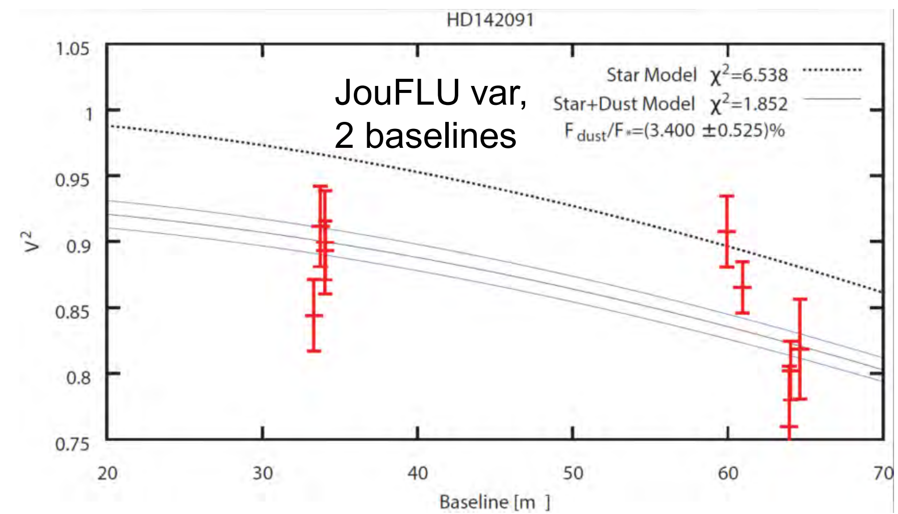
Spectral Type	A	F	G-K	Total
Cold Disk	8	6	6	20
No outer disk	4	7	9	19
Unknown	0	2	0	2
Total	12	15	15	42

Absil data, new DRS





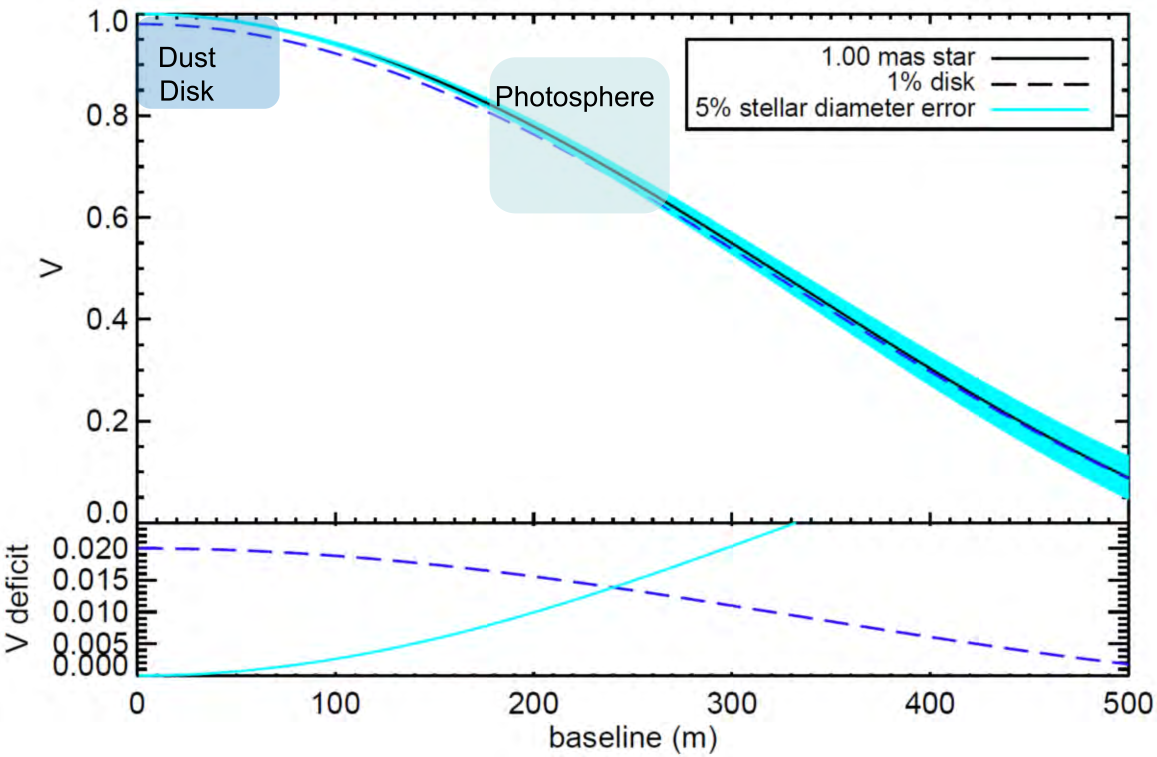




Evolution / Variability

- Dust production mechanism poorly understood
- Close-in dust extremely short lived (yrs)
- Destruction factors:
  - Sublimation, Radiation Pressure, PR drag
- Models:
  - Steady state/trapped nano-grains
  - LHB & outgassing

Wyatt et al. (2008)



Technique:

⇒ Incoherent flux

⇒ Visibility deficit on all baselines

⇒ Easiest to detect at short baselines

⇒ Need <1% precision

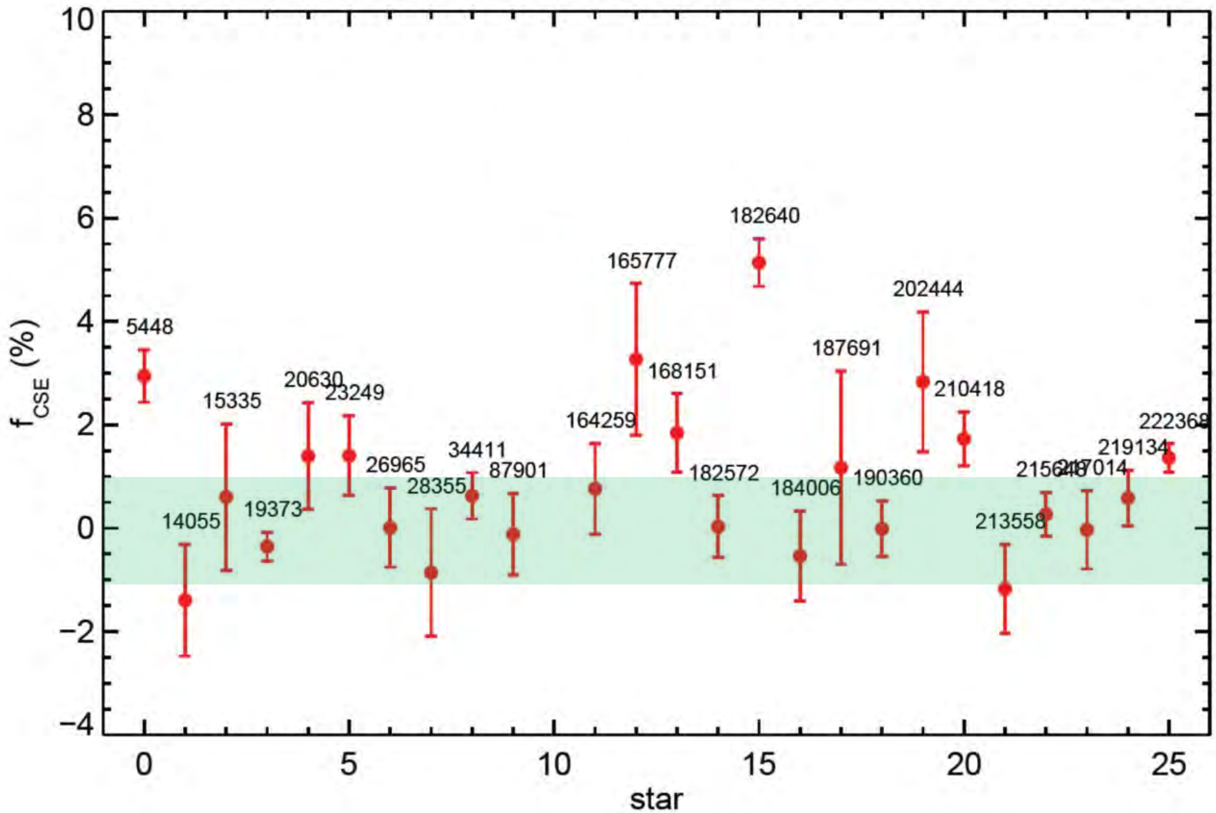
The story unfolds…

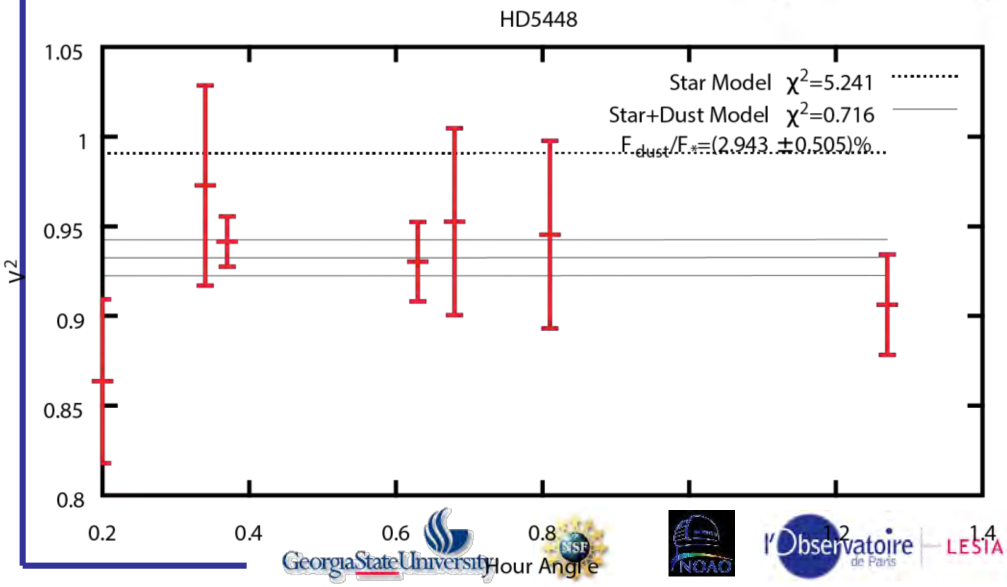
- 2001: Hints of an excess around Vega with PTI. (Ciardi et al. 2001)
- 2004: VLTI/VINCI, upper limits, developed detection method. (di Folco et al. 2004)
- 2006: CHARA/FLUOR detection around Vega, 1:29 0:19% (Absil et al. 2006)
- 2007: FLUOR, del Eri (no detection) & tau Ceti (detection) (di Folco et al. 2007)
- 2008: 5 non-detections & alf Aql (Absil et al. 2008b)
- 2009: bet Leo & eta Lep detections (Akeson et al. 2009)
- 2009: VLTI/VINCI, Fomalhaut (Absil et al. 2009)
- 2011: IOTA/IONIC detection around Vega (Defrère et al. 2011)
- 2011: Palomar Fiber Nuller (PFN) non-detection of Vega (Mennesson et al. 2011a)
- 2011: Coronagraphs see predicted companions (Mawet et al. 2011)
- 2011-12: First spectroscopic detections of very hot excesses (Lisse et al. 2012; Weinberger et al. 2011)
- 2012: VLTI/PIONIER detection around iot Pic (Defrère et al. 2012a)
- 2013: CHARA initial survey of 40+ single MS stars says it is fairly common (11/40) (Absil et al. 2013)
- 2014: VLTI/PIONIER survey, larger VLTI dispersed H-band survey (9/85) (Ertel et al. 2014)

Exozodi Programs

- **Near Infrared Exozodi Variability Study** (complete) Revisit 12 of the bright A-K stars with previously detected excesses from the Absil et al. 42 star FLUOR survey.
- **Near Infrared Exozodi Survey Extension** (in progress) 3 year program observing ≈100 MS A-K stars. Hot dust expected in 30% of systems. Goal is 1% excess detection at 5σ to $m_K < 5$.
- **IRTF/SpeX Spectrophotometric Survey** (in progress) Provide confirmation of dust from NIR excesses, obtain spectra, and develop survey campaign.
- **Monitoring of Known Variable Exozodiacal Disks** (proposed) Revisit three stars from the Exozodiacal Variability survey that exhibit a strong near infrared excess. These stars will be observed at three points during the season.
- **Exozodi confirmation** (proposed) Utilize Speckle interferometry to confirm hosts of exozodis are point sources. Rule out stellar companion from 50 mas to 1+".

Survey Extension





38% show excess

Scott et al. Exozodiacal Survey Extension *(in prep)*

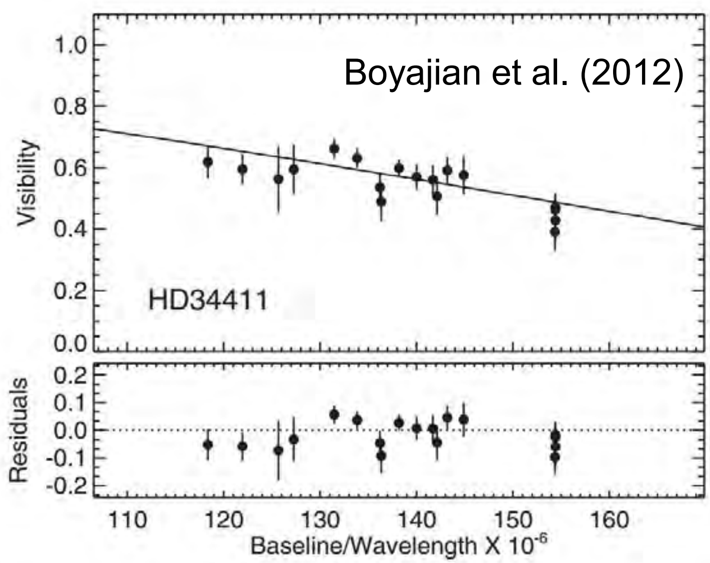
Can we be ``sure'' of Exozodi Variability?

Is the instrument stable?

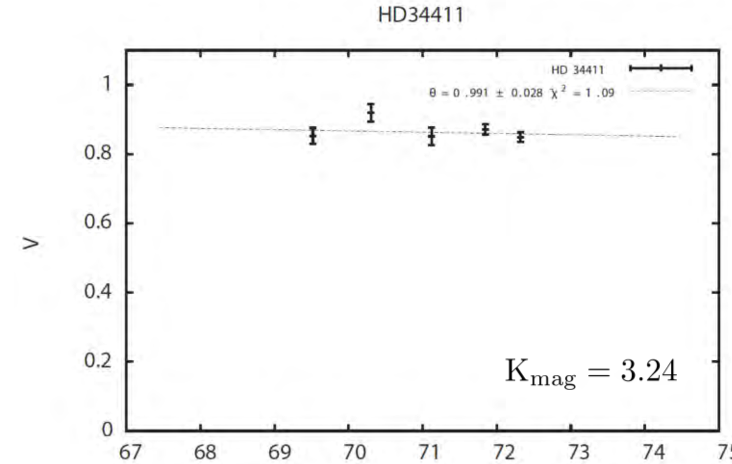
Check diameters independently

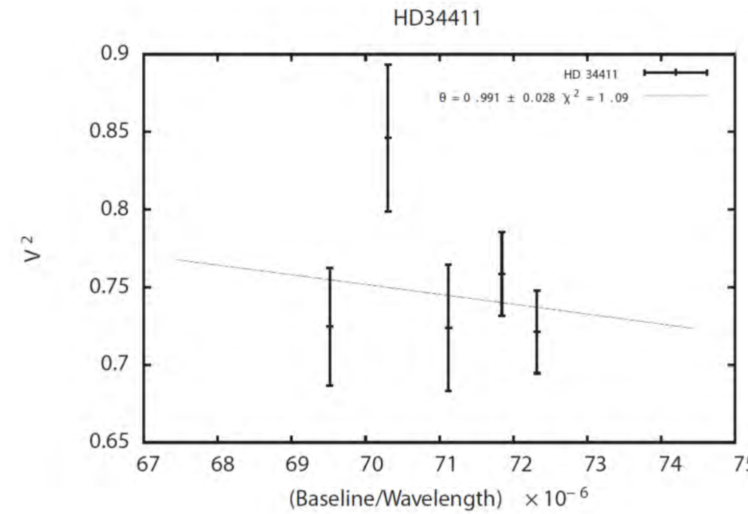
Is the DRS consistent?

Reduce old data with new pipeline



$0.958 \pm 0.015 \qquad \chi^2 = 1.07$



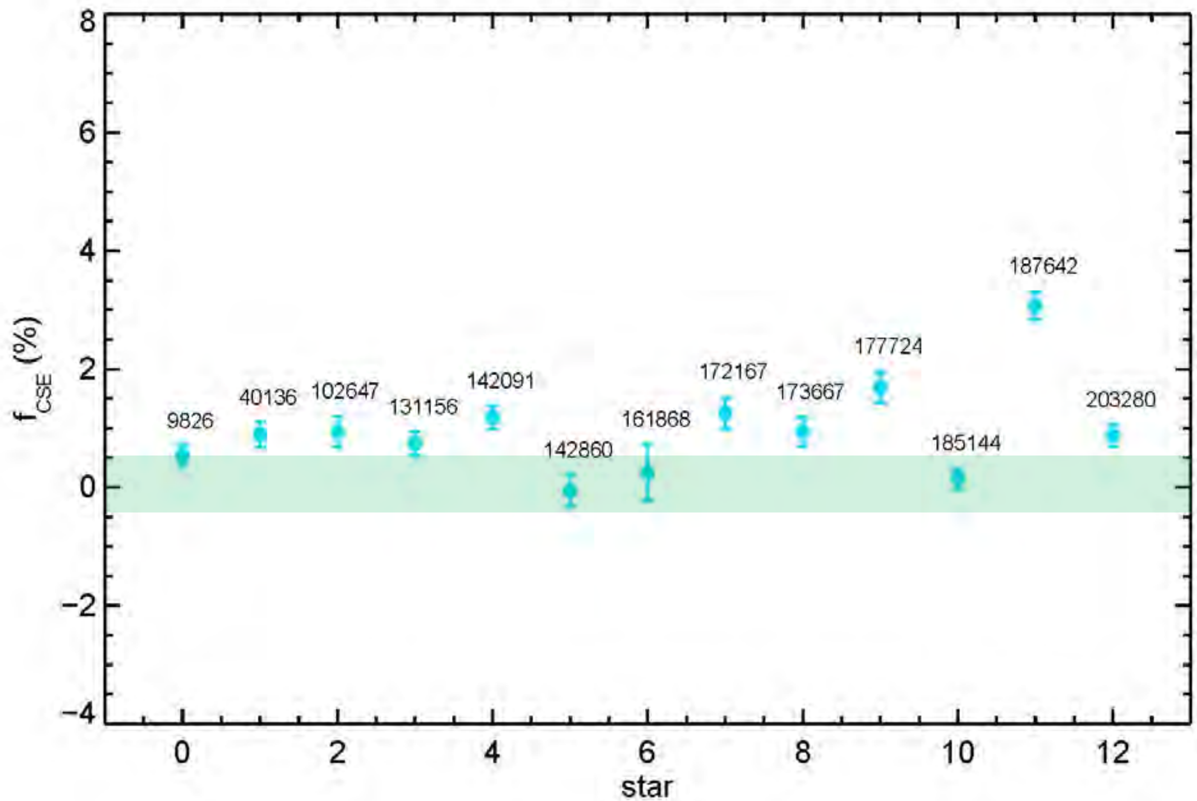


$0.991 \pm 0.028 \qquad \chi^2 = 1.09$

Original survey results

HD	Object	σ^*	excess*
9826	υ And	3.1	n
40136	η Lep	4.2	y
102647	β Leo	3.6	y
131156	ξ Boo	3.7	y
142091	κ CrB	5.9	y
142860	γ Ser	-0.2	n
161868	γ Oph	0.5	n
172167	α Lyr	4.7	y
173667	110 Her	3.8	y
177724	ζ Aql	6.3	y
185144	σ Dra	0.9	n
187642	α Aql	12.8	y
203280	α Cep	4.8	y

* Absil et al. (2013) $\sigma = f_{\mathrm{CSE}}/\sigma_{f_{\mathrm{CSE}}}$



Original survey results
New DRS

HD	Object	σ*	excess*
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102647	β Leo	3.6	y
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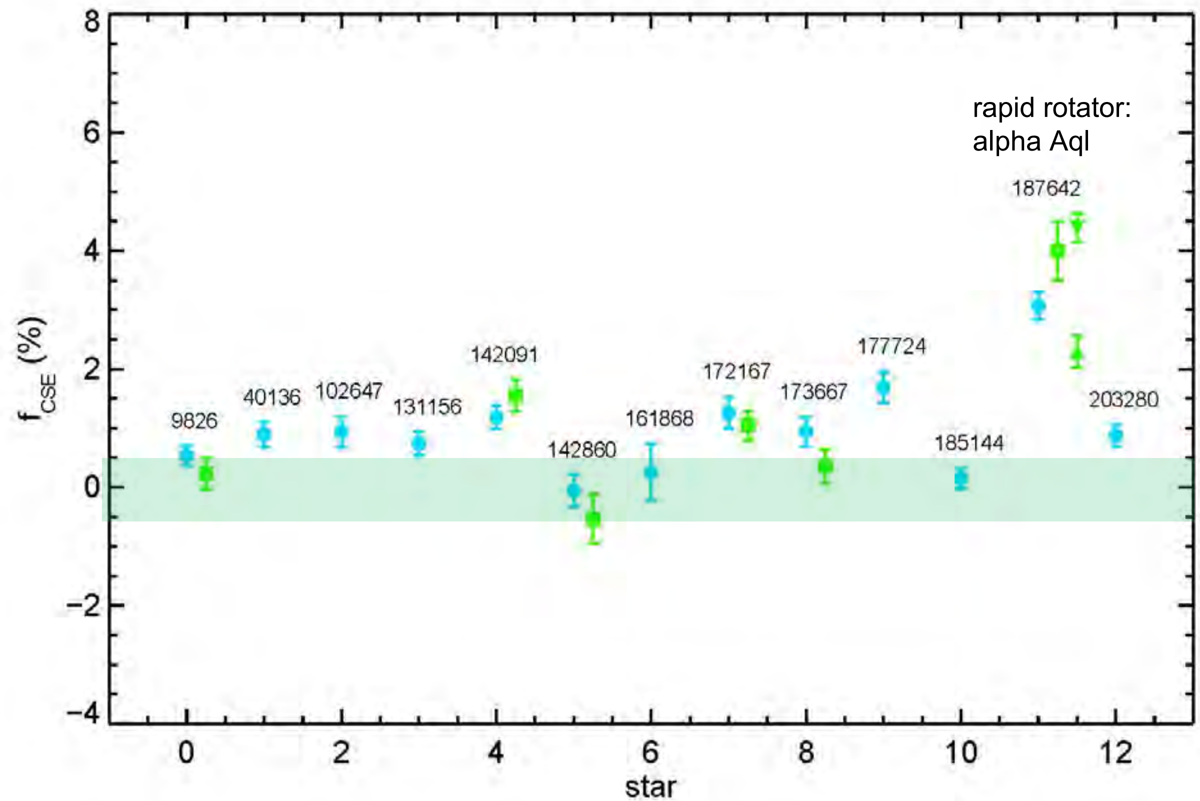
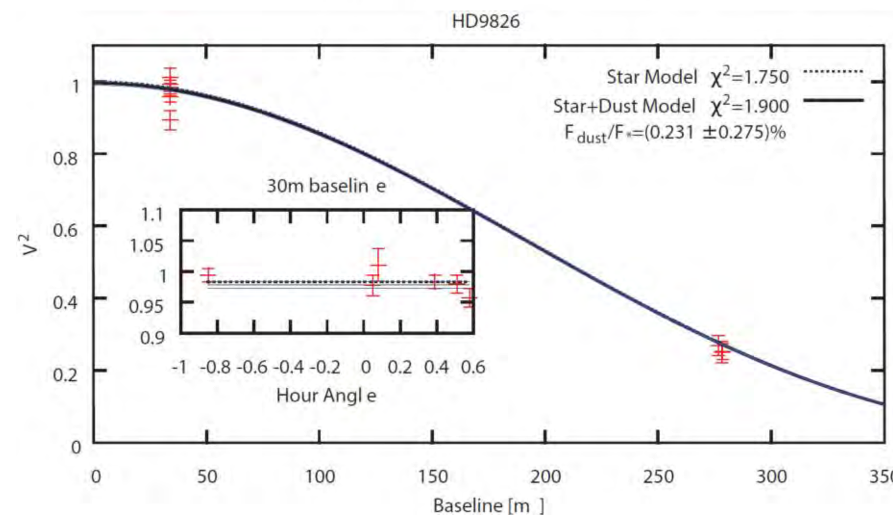




Survey revisited

Previous error bars underestimated, excess significance overestimated

Threshold for detection changed to 1% instead of 0.5%

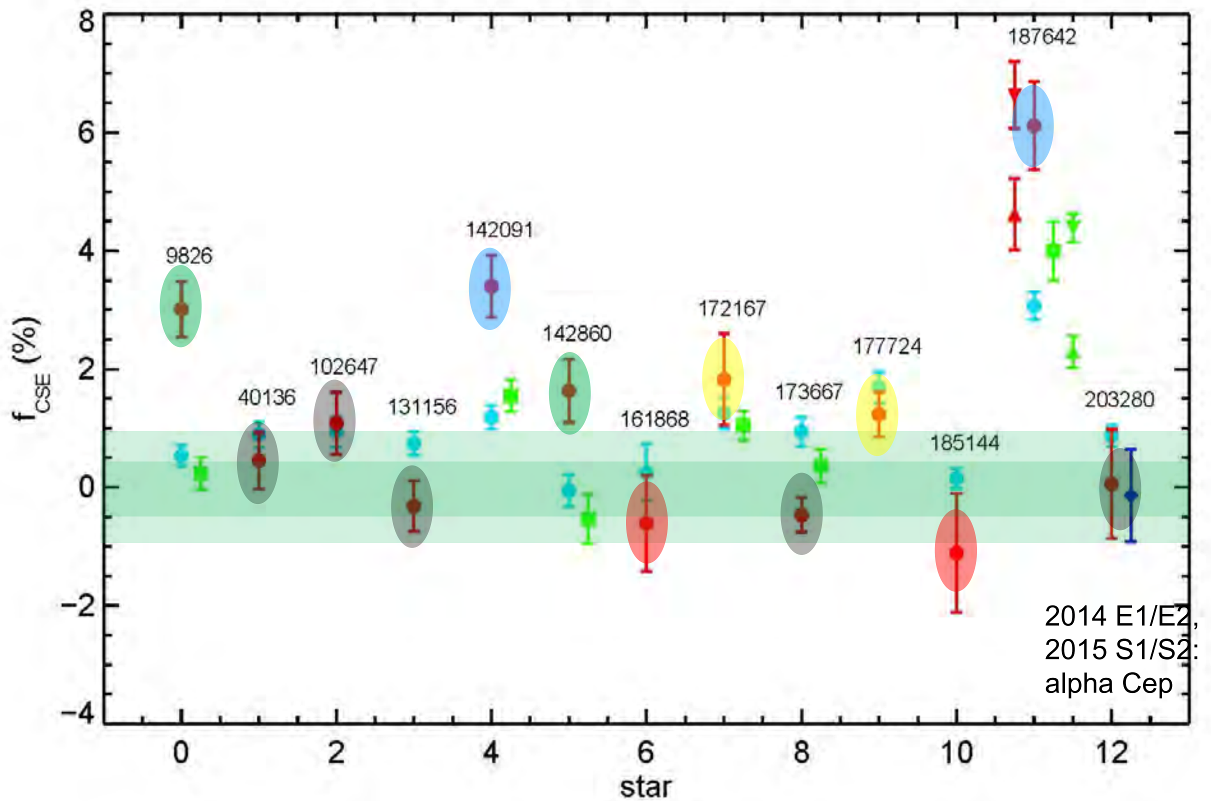
Excesses no longer considered significant: eta Lep, bet Leo, ksi Boo, 110 Her, alf Cep

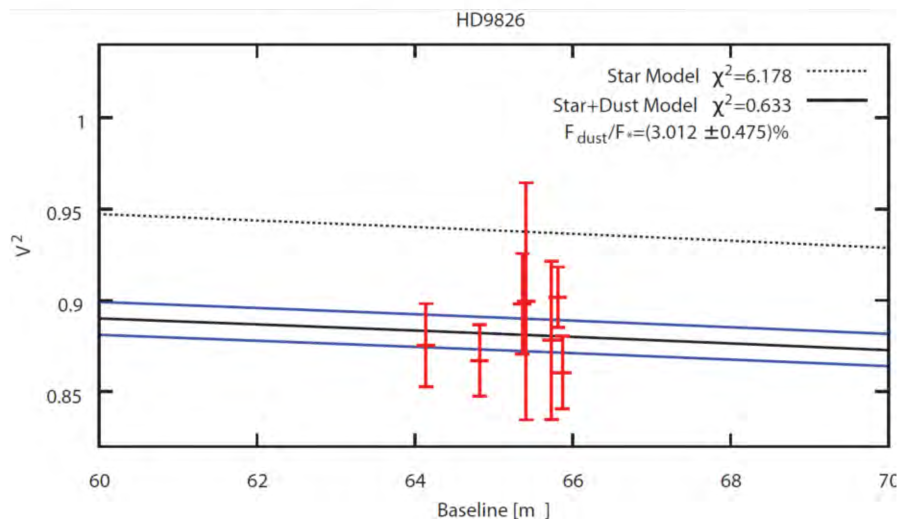
New excesses: ups And, gam Ser

Two excesses remains unchanged: zet Aql, Vega

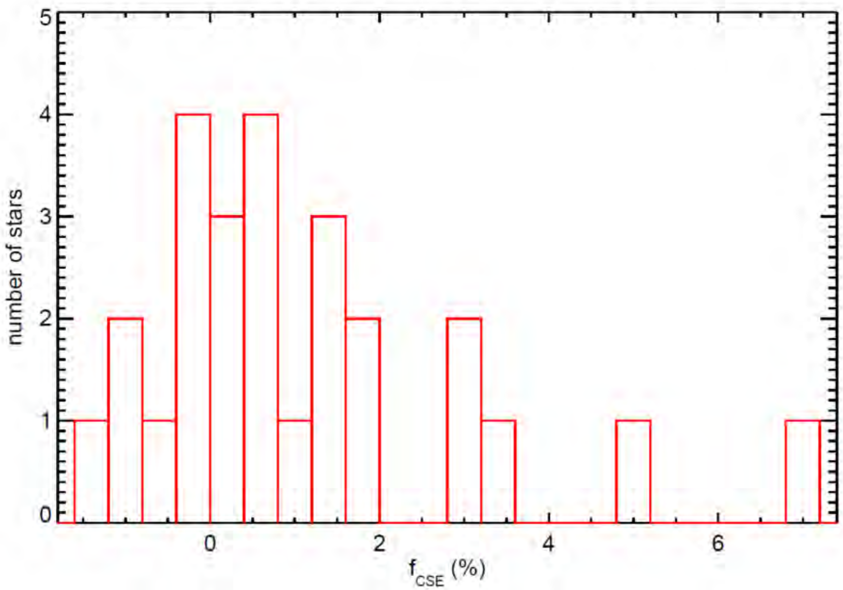
Two non-detections remain unchanged: gam Oph, sig Dra

Two excesses increased: kap CrB, alf Aql





Exozodical disk Variability results



HD	Object	$f_{cse}(\%)^{\dagger}$	$\chi^{2\dagger}$	$f_{cse}(\%)^{\ddagger}$	$\chi^{2\ddagger}$	Δf_{cse}
9826	υ And	0.53 ± 0.17	3.12	3.012 ± 0.475	0.63	2.48 ± 0.50
22484	10 Tau	1.21 ± 0.11	11.00	-2.750 ± 0.730	0.08	-3.96 ± 0.74
40136	η Lep	0.89 ± 0.21	4.24	0.449 ± 0.475	2.03	-0.44 ± 0.52
102647	β Leo	0.94 ± 0.26	3.62	1.087 ± 0.525	0.90	0.15 ± 0.59
131156	ξ Boo	0.74 ± 0.20	3.70	-0.321 ± 0.425	1.40	-1.06 ± 0.47
142091	κ CrB	1.18 ± 0.20	5.90	3.400 ± 0.525	1.85	2.22 ± 0.56
142860	γ Ser	-0.06 ± 0.27	-0.22	1.632 ± 0.535	0.70	1.69 ± 0.60
161868	γ Oph	0.25 ± 0.48	0.52	-0.608 ± 0.810	16.48	-0.86 ± 0.94
172167	α Lyr	1.26 ± 0.27	4.67	1.823 ± 0.775	16.99	0.56 ± 0.82
173667	110 Her	0.94 ± 0.25	3.76	-0.467 ± 0.295	14.20	-1.41 ± 0.39
177724	ζ Aql	1.69 ± 0.27	6.26	1.230 ± 0.380	1.32	-0.46 ± 0.47
185144	σ Dra	0.15 ± 0.17	0.88	-1.109 ± 1.000	1.88	-1.26 ± 1.01
187642	α Aql	3.07 ± 0.24	12.90	6.115 ± 0.740	2.76	3.05 ± 0.78
203280	α Cep	0.87 ± 0.18	4.70	-0.139 ± 0.780	0.74	-1.01 ± 0.80

† Absil et al. (2013)
‡ this work

HD	Object	σ^*	excess*	σ^{**}	excess**
9826	υ And	3.1	n	6.3	y
40136	η Lep	4.2	y	0.9	n
102647	β Leo	3.6	y	2.1	n
131156	ξ Boo	3.7	y	-0.8	n
142091	κ CrB	5.9	y	6.5	y
142860	γ Ser	-0.2	n	3.1	y
161868	γ Oph	0.5	n	-0.8	n
172167	α Lyr	4.7	y	2.4	—
173667	110 Her	3.8	y	-1.6	n
177724	ζ Aql	6.3	y	3.2	y
185144	σ Dra	0.9	n	-1.1	n
187642	α Aql	12.8	y	8.3	y
203280	α Cep	4.8	y	-0.2	n

* Absil et al. (2013)
** this work

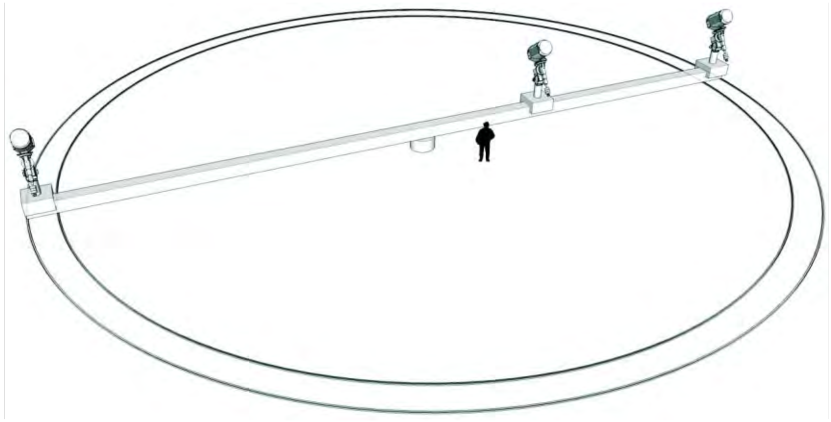
$$\sigma = f_{\mathrm{CSE}}/\sigma_{f_{\mathrm{CSE}}}$$

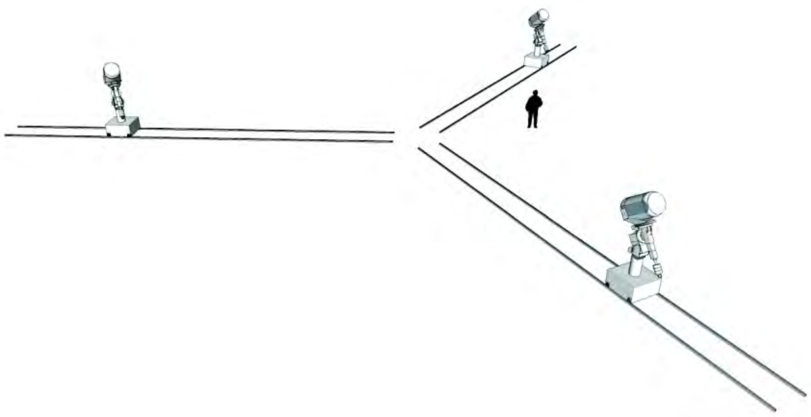
79% vs 36%

Scott et al. The Variability of Exozodiacal Dust *(in prep)*

TeRMINALS: ThiRty Meter INterferometer Array for exozodiacaL duSt

- 3+ 0.2-0.5m commercial scopes
- Rail-mounted → variable baselines
- Off-the-shelf, low-cost priority
- Open air or fiber-based combination
- Y-config would need patch cord delay+OPLE
- Linear array wouldn't need delay
- NSF or NASA proposal?





Item	Cost (x $1000)	Notes
Telescopes (each)	10	Celestron or Meade 14"
	20/30	0.3/0.4 m Officina Stellare
	15/22/32.5/50	Planewave 14"/17"/20"/24"
	20/25/30/40/65	RC Optical Systems 12.5/16/20/24"
Mounts (each)	20-27	Astro-Physics 3600GTO
Auto-Guider (each)	1.2	SBIG SG-4
Optical table	∼10	
Mounts, mechanics	∼50	
Optics	∼50	
Active delay	∼100	Newport XPS+motion stages
Fibers	∼50	
Construction	∼150	
Enclosure	∼10	
Detector	—	
Total	∼500k-700k	not including detector or integrated optics components

in summary……

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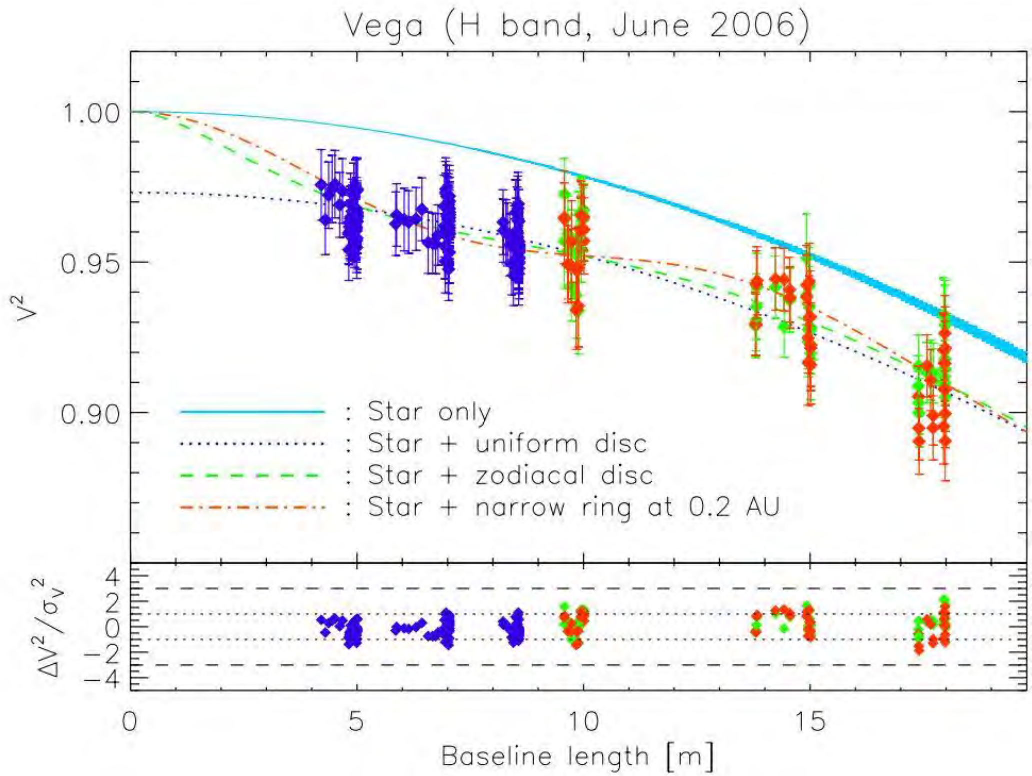
Disk architecture

- Need very high precision at very short baselines
- Regime between long-baseline interferometry and aperture-masking
- Time consuming
- How to reveal morphology of disk and how dust is changing?



Defrère et al. (2011)

Variability Survey Log

HD	Object	Obs date	Baseline	Number of scans	Notes
9826	υ And	10/15/2013, 10/16/2013	E1-E2	9	
22484	10 Tau	7/22/2014, 11/10/2014	S1-S2	7	$\sim$-3% (non-physical) excess with a > 3 sigma significance. Bad calibration, only 4 points.
40136	η Lep	10/13/2014, 11/10/2014	S1-S2	9	
102647	β Leo	5/1/2015, 5/27/2015, 5/28/2015	S1-S2	20	
131156	ξ Boo	5/1/2015	S1-S2	8	
142091	κ CrB	5/1/2015, 6/18/2015, 6/19/2015, 6/20/2015	S1-S2,E1-E2	17	
142860	γ Ser	5/15/2013, 5/25/2014, 6/16/2015	E1-E2	22	No excess found by Absil et al. (2013), but we find one.
161868	γ Oph	6/17/2015	S1-S2,E1-E2	8	No excess found by Absil, and none found with E1-E2. Poor calibration.
172167	α Lyr	7/22/2014, 5/27/2015, 8/14/2015	S1-S2	21	
173667	110 her	6/16/2015	S1-S2	16	data suggest binary in WDS, but min separation $> 20''$
177724	ζ Aql	6/18/2015	E1-E2	9	
185144	σ Dra	8/15/2015	S1-S2	4	new object to var list. Absil et al. (2013) detected no excess, we confirm that.
187642	α Aql	7/23/2014, 6/17/2015	E1-E2,S1-S2	15	minimum and maximum UD models and fast rotator model from (Monnier et al. 2007).
203280	α Cep	07/20/2014, 7/23/2014, 11/10/2014, 11/6/2014, 8/13/2015, 8/15/2015	E1-E2 E1-E2 S1-S2	30	2014 data use E1-E2. 2015 data use S1-S2. Fast rotator model used from (van Belle et al. 2006).

Survey Extension Results

HD	Object	Obs date	Baseline	Number of data points	$f_{cse}(\%)$	χ^2	σ
5448	37 And	8/13/2015, 8/14/2015	S1-S2	5	2.943 ± 0.505	0.716	5.8
14055	γ Tri	10/11/2013, 10/14/2013	E1-E2	12	-1.396 ± 1.080	0.891	-1.3
15335	13 Tri	10/16/2013, 10/19/2013	E1-E2	7	0.605 ± 1.415	0.651	0.4
19373	ι Per	10/13/2014	S1-S2	8	-0.356 ± 0.280	2.267	-1.3
20630	κ01 Cet	10/17/2013, 10/18/2013	E1-E2	7	1.393 ± 1.030	0.830	1.4
23249	δ Eri	10/11/2013, 10/14/2013	E1-E2	11	1.404 ± 0.770	0.092	1.8
26965A	40 Eri	10/13/2014	S1-S2	8	0.011 ± 0.765	1.945	0.0
28355	b Tau	10/12/2013, 10/18/2013	E1-E2	11	-0.860 ± 1.235	4.157	-0.7
34411	λ Aur	10/16/2013, 10/17/2013	E1-E2	12	0.626 ± 0.450	0.797	1.4
87901	α Leo	11/10/2014	S1-S2	6	-0.118 ± 0.790	0.539	-0.1
162003A	ψ01 Dra A	7/23/2014	E1-E2	6	7.005 ± 0.525	1.431	13.3
164259	ζ Ser	6/15/2015	E1-E2	10	0.761 ± 0.880	2.748	0.9
165777	72 Oph	6/19/2015, 6/20/2015	E1-E2	12	3.269 ± 1.465	1.464	2.2
168151	36 Dra	7/23/2014	E1-E2	6	1.842 ± 0.760	3.301	2.4
182572	b Aql	7/23/2014, 6/15/2015, 6/20/2015	E1-E2	6	0.030 ± 0.600	2.336	0.1
182640	δ Aql	10/13/2014	S1-S2	8	5.138 ± 0.460	1.837	11.2
184006	ι Cyg	6/20/2015	E1-E2	6	-0.539 ± 0.875	1.581	-0.6
187691A	o Aql	6/20/2015	E1-E2	8	1.171 ± 1.870	0.478	0.6
190360	LHS 3510	10/16/2013, 10/19/2013	E1-E2	8	-0.012 ± 0.540	1.457	0.0
202444	τ Cyg	11/12/2014	S1-S2	5	2.833 ± 1.350	3.439	2.1
210418	θ Peg	10/12/2013, 10/14/2013	E1-E2	8	1.727 ± 0.520	2.879	3.3
213558	α Lac	10/11/2013, 10/12/2013	E1-E2	11	-1.172 ± 0.860	0.428	-1.4
215648	LHS 3851	8/13/2015	S1-S2	10	0.269 ± 0.420	3.701	0.6
217014	51 Peg	10/16/2013, 10/19/2013	E1-E2	9	-0.032 ± 0.760	0.624	0.0
219134	HR 8832	10/13/2014	S1-S2	8	0.582 ± 0.540	1.614	1.1
222368	ι Sc	10/17/2013, 10/18/2013	E1-E2	8	1.360 ± 0.275	1.549	4.9