

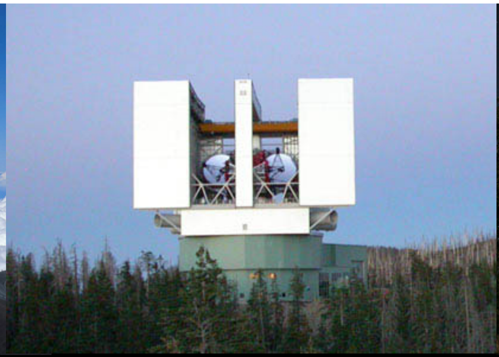


Some Astronomical Applications of High accuracy Stellar Interferometry

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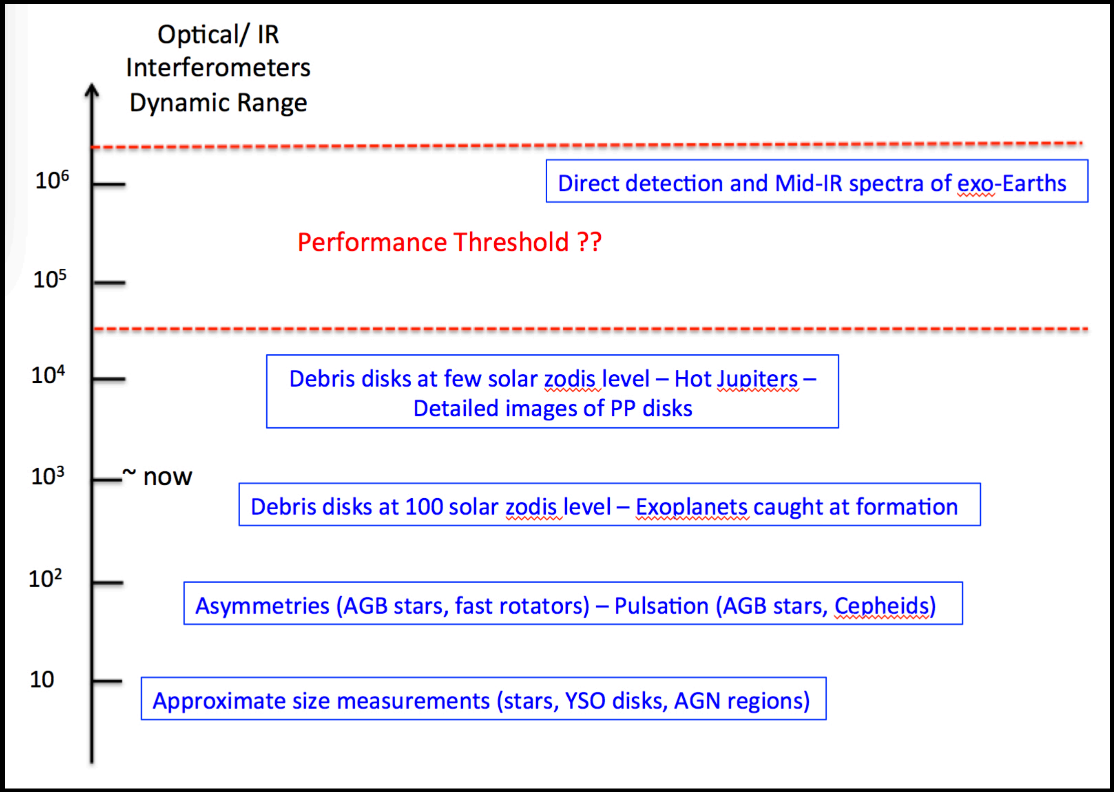
INTEREST OF HIGH DYNAMIC RANGE OBSERVATIONS

- One of Dave Buscher's 4 bullets for major technical upgrades, but for what science?

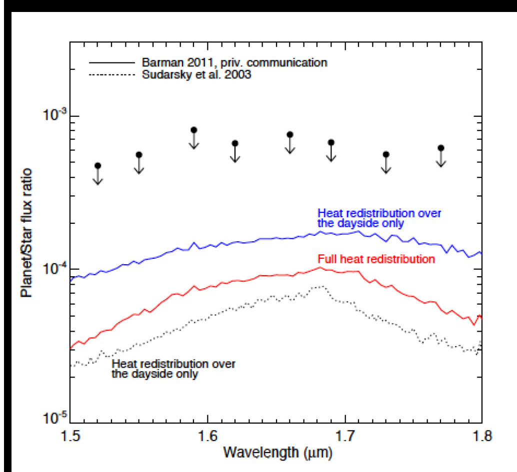
- Assuming enough baselines, angular resolution and sensitivity, what would then be the contrast threshold (if any) for "great science" ?

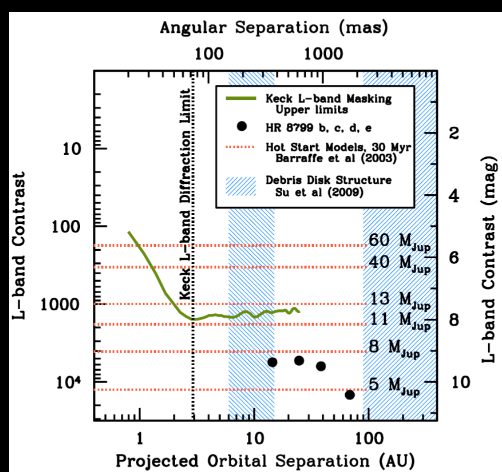


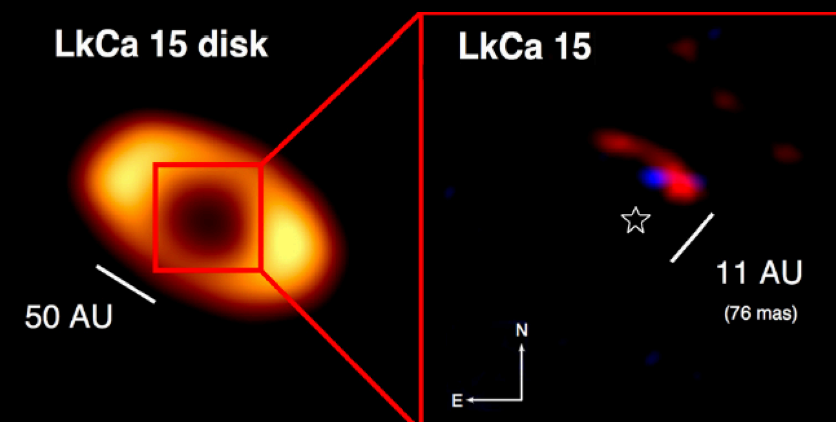
HIGH CONTRAST : PHASE

➢ High Accuracy Phase Measurements, essentially Closure Phase
(also CP nulling, DP, DCP, and other differential phase observables, but not discussed here)

- Single telescope aperture masking: detection limits from a few 100:1 to ~1000:1 at H/K/L (Keck NRM: Kraus and Ireland ApJ 2012, Hinkley et al. ApJ 2011; VLT NACO/SAM: Huelamo et al. A&A 2011)
- Long baseline interferometry at H band: ~ 1000:1 as well (VLTI/PIONIER: Absil et al. 2011 A&A, MIRC: Zhao et al. PASP 2011)
- Can not detect centrally symmetric structures (clumps and companions OK, but misses the main component of disks)





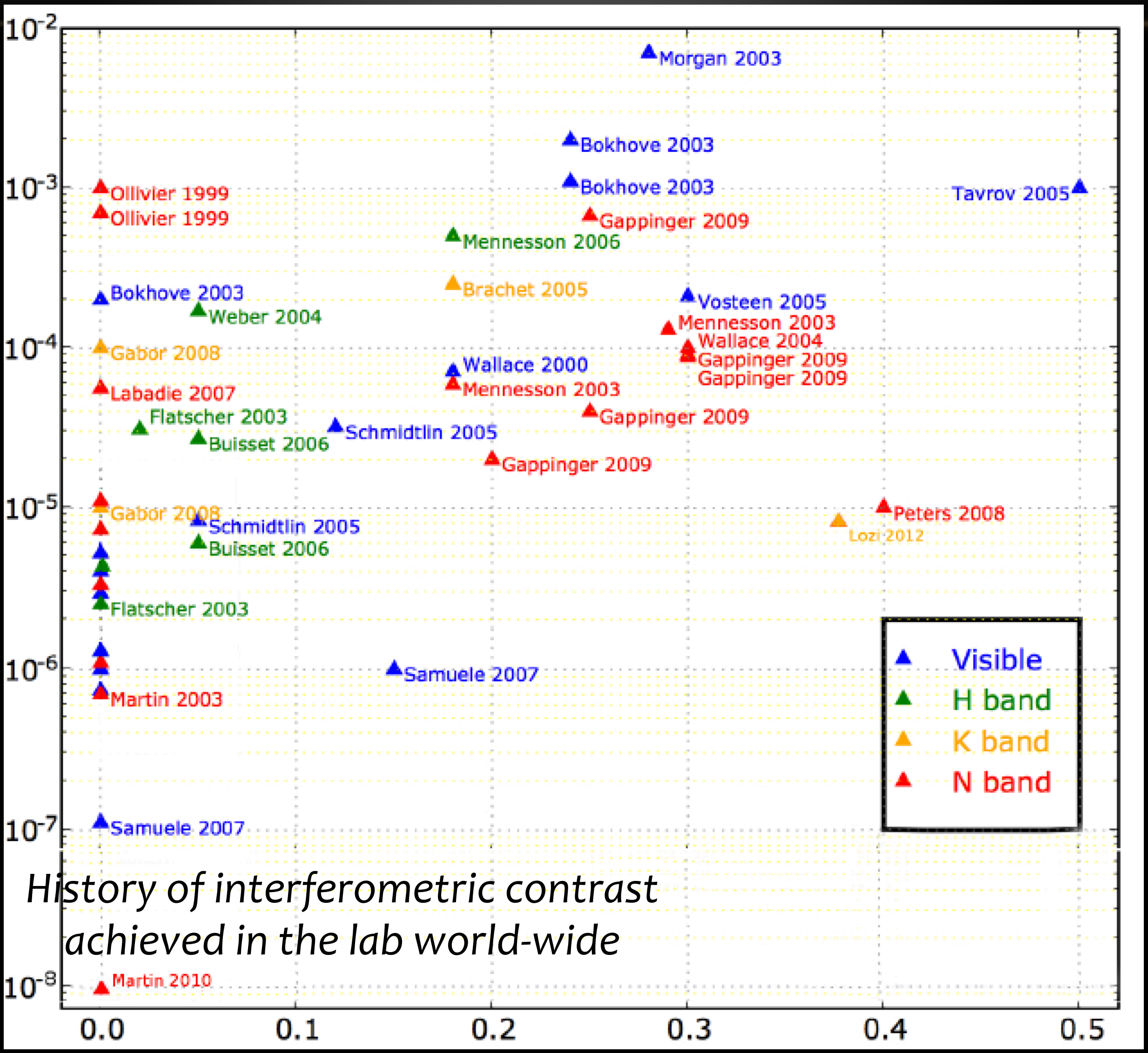


High contrast: amplitude

➢ High Accuracy Visibility Amplitude Measurements

- Long baseline interferometry at K band: FLUOR on IOTA and then on CHARA
  ~ 200:1 to 500:1 (Perrin et al. 2004 A&A, Merand et al. 2007 ApJ, Absil et al. A&A 2013)
- Long baseline Nulling Interferometry at N band (KI: Millan-Gabet et al. 2012, Mennesson et al. 2013 ApJ)
- Single telescope "dual aperture masking" nulling: detection limits around 1000:1 at K band
  (Palomar Fiber Nuller: Mennesson et al. ApJ 2011a & 2011b)
- Near future at CHARA and at LBTI
- Can detect centrally symmetric structures but can not disentangle between disks and point sources without ancillary data (CP data, disk inclination…)
- One possible route for high contrast is to keep system visibility very close to 1 → very deep nulling, working great in the lab, even broad-band

In a perfect world

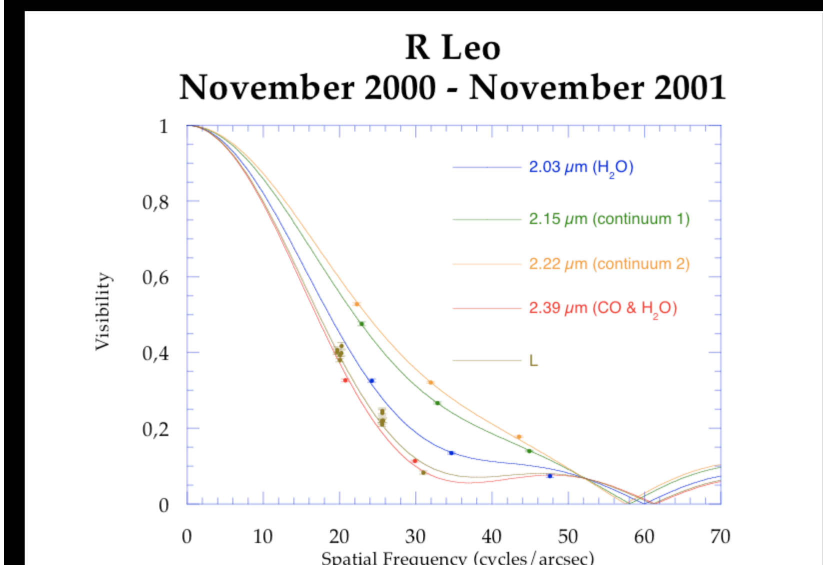


History of interferometric contrast achieved in the lab world-wide

Interferometric Observations of late type stars
IOTA (FLUOR + TISIS: 1998-2005)

- 1% ish Visibility accuracies – Very low spectral resolution
- Enough to correlate observed visibility fluctuations with absorption features due to extended molecular layers (Mennesson et al. ApJ 2003, Perrin et al. A&A 2004)

$R_* = 10.94 \pm 0.85$ mas **$R_{layer} = 25{,}00 \pm 0{,}17$mas** **Phase K: 0.79**
$T_* = 3856 \pm 119$ K **$T_{layer} = 1598 \pm 24$ K** **Phase L: 0.64**



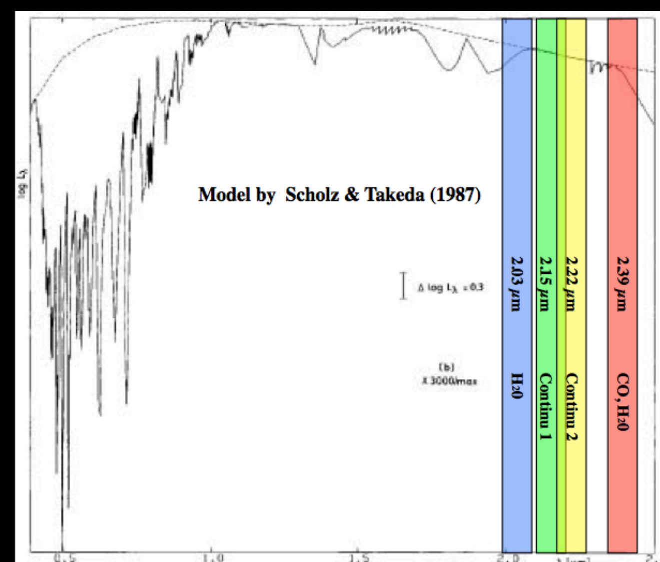
$\tau_{2.03\mu m} = 1.19 \pm 0.01$

$\tau_{2.15\mu m} = 0.51 \pm 0.01$

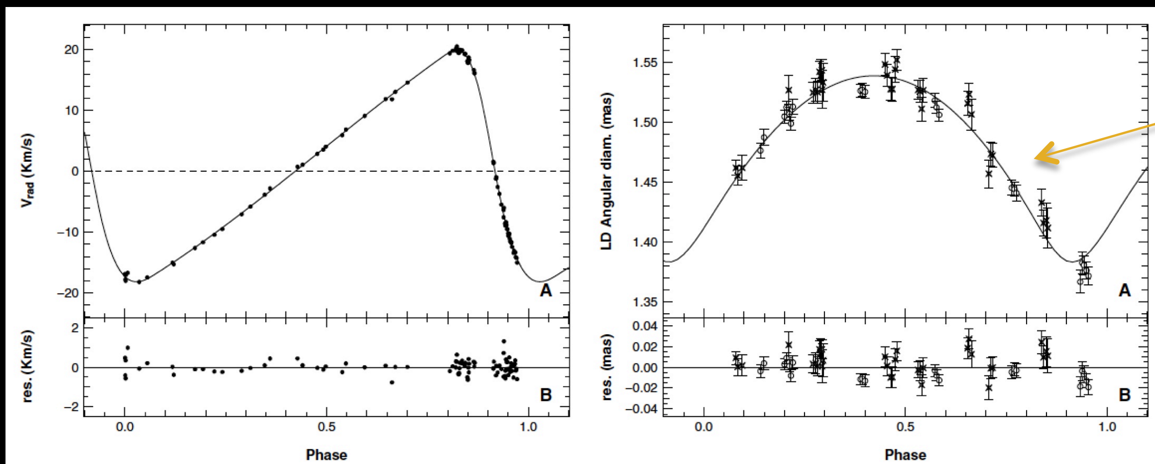
$\tau_{2.22\mu m} = 0.33 \pm 0.01$

$\tau_{2.39\mu m} = 1.37 \pm 0.01$

$\tau_{L} = 0.63 \pm 0.01$



CEPHEIDS OBSERVATIONS (MERAND ET AL. 2005 A&A)



CHARA long baseline + FLUOR visibility accuracy

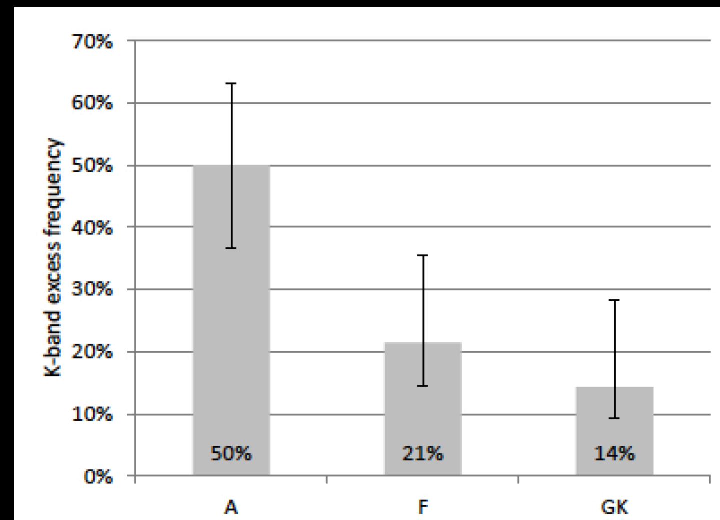
Baade – Wesselink equation:

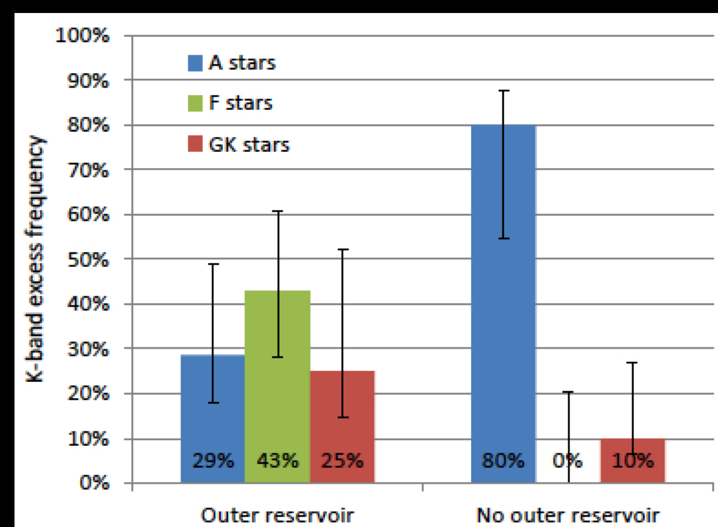
$$\theta(T) - \theta(0) = -2\,\frac{p}{d}\int_0^T \left(V_{\mathrm{rad.}}(t) - V_\gamma\right)\mathrm{d}t$$

δ Cep: known distance d, measured diameter pulsation and radial velocity
→ p factor = 1.27 +/- 0.06 → calibrates Cepheids P – (absolute) L relation

CHARA /FLUOR HOT DEBRIS DISKS OBSERVATIONS (ABSIL ET AL. 2013, A&A)

Name	f_{CSE} (%)	σ_{f} (%)	χ^2_{f}	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
del UMa	0.37	0.37	2.11	1.0	NO
eta Crv[b]	0.37	0.54	1.19	0.7	NO
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





CHARA /FLUOR HOT DEBRIS DISKS OBSERVATIONS: EXTENSION TILL 2016 (PARTIALLY FUNDED THROUGH NASA OSS GRANT)

- **Expand current FLUOR survey of 42 MS stars to ~100 stars,** with sensitivity to (~2X) fainter exozodi emission

- **Statistical analysis of hot dust phenomenon, studying dependency on basic stellar parameters** such as the existence of cold dust (MIR /FIR excess), stellar spectral type and age

- **Look for correlation of the excess with the presence of massive planets** previously detected by RV or transit studies.

- **Study the short term evolution of the detected excess**,

- **Constrain the morphology of these hot debris disks**, (different baselines)

- **Develop new models and numerical simulations of the dynamical evolution of small hot dust grains**, including the effect of gas/dust coupling close to the dust sublimation radius

- **Study the wavelength dependence & nature of the excess via:**
  - spectrally resolved observations in the Kband (improved FLUOR will have 8 channels)
  - complementary high contrast high resolution observations w/ other instruments (MIRC/NIRC/ Palomar / LBTI)

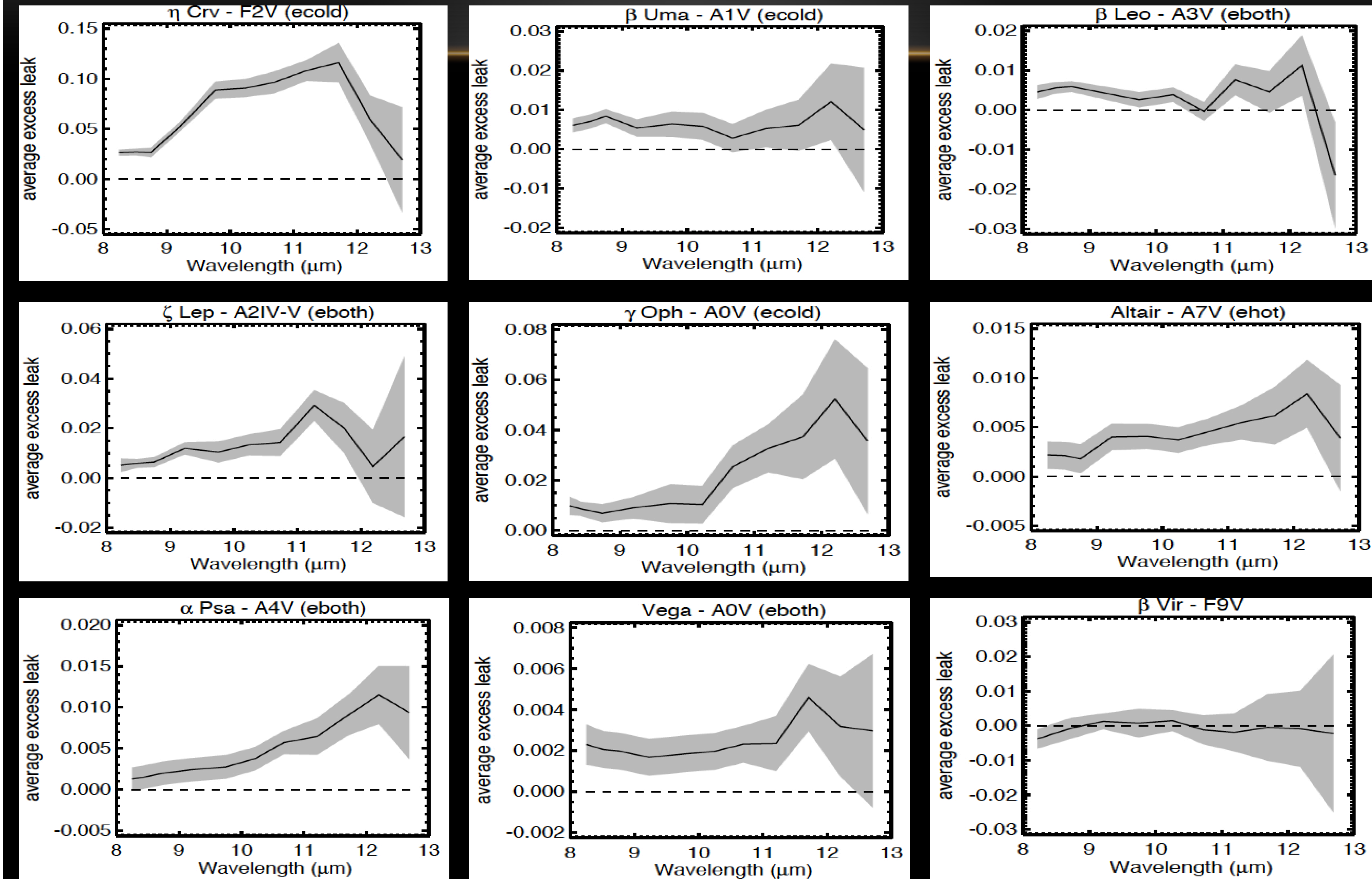
Results from KIN exo-zodi surveys of 41 nearby single MS stars (Mennesson & Millan-Gabet 2013)

Star	Spectral Type	8-9 μm xs	8-9 μm xs uncertainty	snr8-9	8-13 μm xs	8-13 μm xs uncertainty	snr8-13	Detected Far IR Excess	Detected NIR Excess
107_psc	K1V	0.0020	0.0030	0.67	0.0083	0.0068	1.23	N	N
1_ori	F6V	0.0030	0.0021	1.41	0.0017	0.0034	0.5	N	N
47_uma	G1V	0.0014	0.0028	0.5	-0.0018	0.0053	-0.34	N	N
70_oph	K0V	0.0012	0.0022	0.56	-0.0011	0.0028	-0.39	N	N
HIP54035	M2V	-0.0004	0.0025	-0.16	-0.0026	0.0052	-0.5	N	N
bet_com	G0V	0.0058	0.0048	1.2	0.0030	0.0060	0.5	N	N
bet_vir	F9V	-0.0021	0.0030	-0.7	-0.0004	0.0033	-0.11	N	N
chi1_ori	G0V	-0.0009	0.0027	-0.34	-0.0008	0.0036	-0.23	N	N
eta_crv	**F2V**	**0.0270**	**0.0032**	**8.35**	**0.0443**	**0.0051**	**8.69**	**Y**	**N**
gam_lep	F6V	-0.0030	0.0018	-1.67	-0.0011	0.0024	-0.46	N	N
gamma_oph	**A0V**	**0.0087**	**0.0028**	**3.08**	**0.0113**	**0.0051**	**2.22**	**Y**	**N**
gamma_ser	F6IV	-0.0044	0.0023	-1.87	-0.0033	0.0037	-0.9	N	N
iota_per	F9V	-0.0045	0.0025	-1.82	-0.0003	0.0037	-0.07	N	N
iota_psc	F7V	0.0024	0.0030	0.79	0.0082	0.0048	1.71	N	N
kap1_cet	G5V	-0.0036	0.0036	-0.98	-0.0085	0.0061	-1.39	N	N
kx_lib	K4V	0.0035	0.0025	1.38	-0.0011	0.0049	-0.23	N	N
lam_aur	G1IV-	0.0062	0.0030	2.06	0.0056	0.0062	0.91	N	N
nsv_4765	K8V	-0.0046	0.0030	-1.53	-0.0031	0.0063	-0.5	N	N
tau_boo	F6IV	0.0031	0.0021	1.46	0.0021	0.0045	0.47	N	N
the_per	F7V	-0.0016	0.0028	-0.56	0.0004	0.0045	0.08	N	N
ups_and	F9V	-0.0011	0.0031	-0.34	-0.0008	0.0052	-0.16	N	N
61_vir	G7V	0.0051	0.0030	1.7	0.0046	0.0066	0.69	N	N
69_uma	A3V	-0.0039	0.0030	-1.31	-0.0002	0.0062	-0.03	N	N
70_vir	G5V	0.0040	0.0022	1.84	0.0056	0.0035	1.6	N	N
beta_leo	**A3V**	**0.0056**	**0.0014**	**3.96**	**0.0042**	**0.0019**	**2.21**	**Y**	**Y**
alp_psa	**A4V**	**0.0015**	**0.0014**	**1.05**	**0.0037**	**0.0016**	**2.34**	**Y**	**Y**
beta_cas	F2IV	0.0021	0.0020	1.03	0.0017	0.0022	0.77	Y	N
beta_uma	**A1V**	**0.0071**	**0.0018**	**4.02**	**0.0064**	**0.0025**	**2.54**	**Y**	**N**
delta_uma	A3V	0.0065	0.0041	1.59	0.0089	0.0056	1.58	Y	N
eps_eri	K2V	0.0025	0.0012	2.16	0.0018	0.0014	1.26	Y	N
eta_lep	F2V	-0.0006	0.0017	-0.32	-0.0039	0.0028	-1.37	Y	N
zeta_lep	**A2IV**	**0.0059**	**0.0018**	**3.3**	**0.0096**	**0.0031**	**3.12**	**Y**	**Y**
tau_ceti	G8V	-0.0011	0.0021	-0.53	-0.0008	0.0033	-0.25	Y	Y
vega	**A0V**	**0.0021**	**0.0009**	**2.3**	**0.0022**	**0.0010**	**2.13**	**Y**	**Y**
eta_cas_A	G3	0.0031	0.0020	1.55	0.0033	0.0027	1.21	N	Y
alf_cep	A7IV	0.0003	0.0020	0.17	0.0009	0.0027	0.34	N	Y
zet_aql	A0V	0.0036	0.0044	0.82	0.0018	0.0050	0.36	N	Y
lam_gem	A3V	-0.0030	0.0030	-1	-0.0041	0.0061	-0.67	N	Y
10_Tau	F8V	0.0076	0.0041	1.84	0.0024	0.0088	0.28	N	Y
Altair	**A7V**	**0.0021**	**0.0014**	**1.5**	**0.0038**	**0.0015**	**2.55**	**N**	**Y**
kappa_crb	K1IV	0.0035	0.0044	0.8	0.0064	0.0059	1.08	N	Y

Red: detected KIN excess
Blue: likely KIN excess

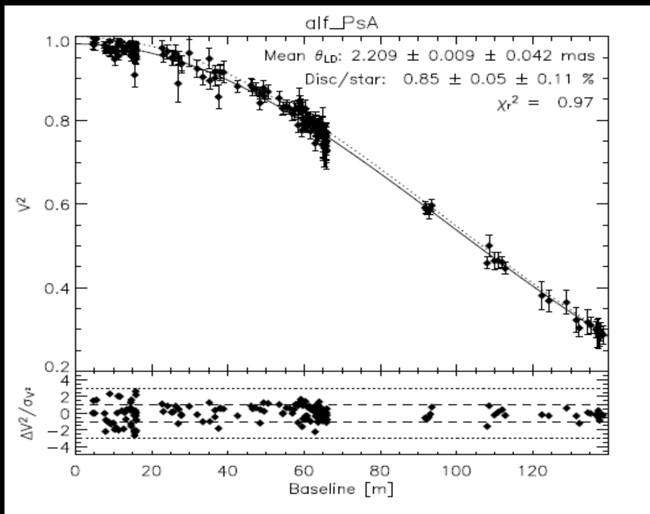
- Extends RMG 2011 analysis paper (full N-band, 25 → 41 stars)
- Strong spectral dependence of detected excess (age effect ?)
- Strong correlation with far IR excess (cold dust)
- Only 2 (to 4) of the 12 NIR excess stars show a KIN MIR excess
- Best 1-σ excess detection limit is 0.1% (typical is 0.2-0.3%)

INDIVIDUAL STAR RESULTS

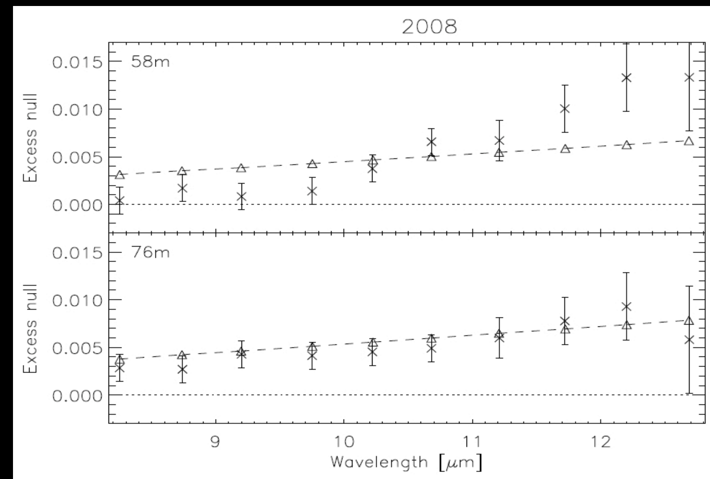


High contrast interferometric observations of debris diks: Fomalhaut

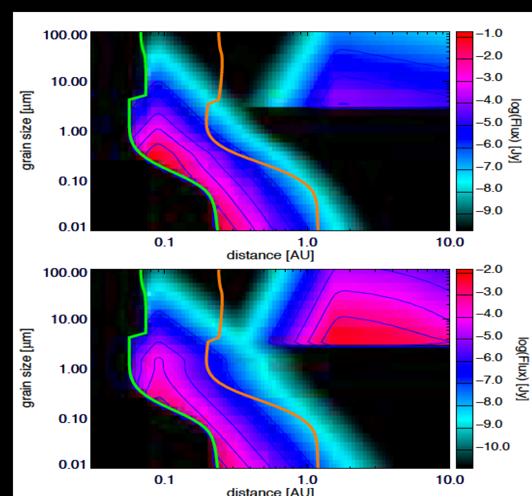
VLTI /VINCI: Absil, Mennesson, Lebouquin et al. 2009



KIN: Mennesson, Absil, Lebreton et al. ApJ 2013



Lebreton et al. A&A 2013



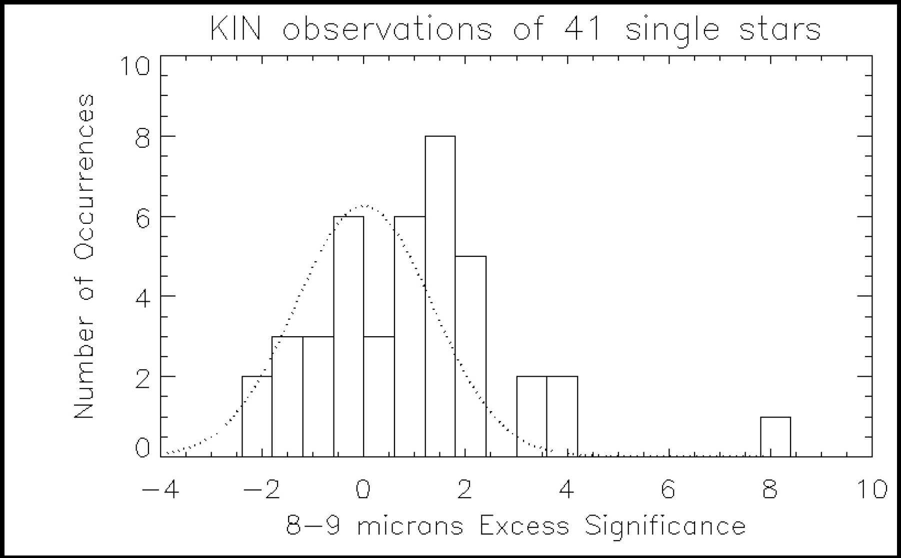
λ = 2 μm

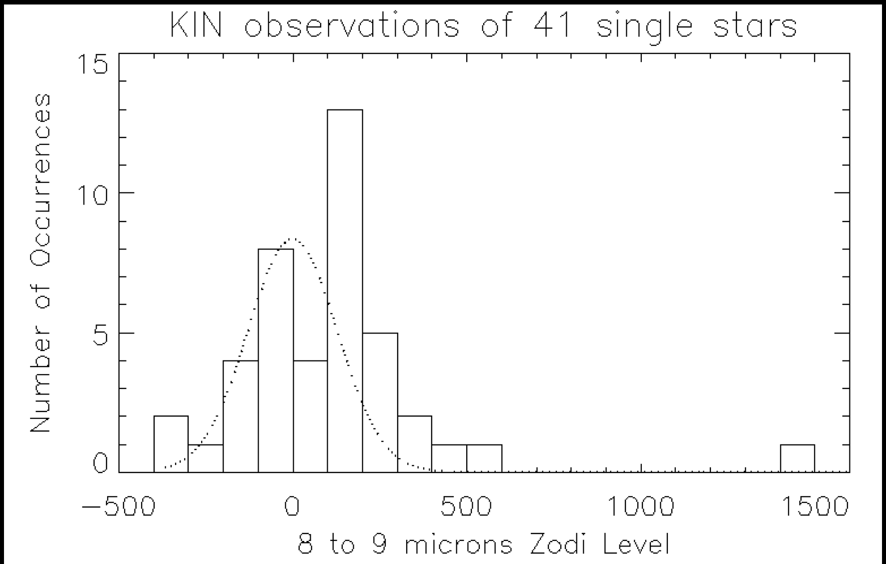
λ = 10 μm

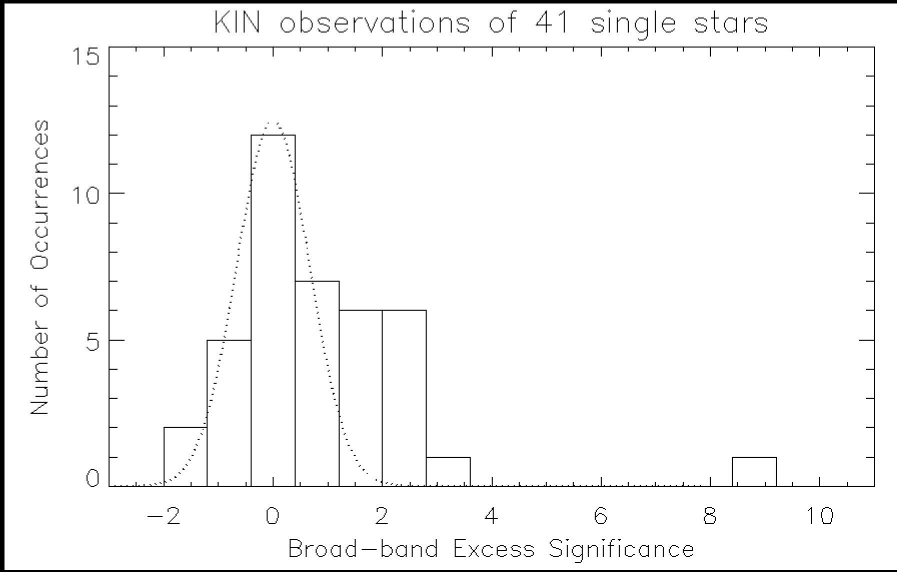
Radiative modeling of multi-wavelength interferometric data (GrateR, Augereau, Lebreton) suggests two distinct dust populations:

- (1) a population of very small (0.01 to 0.5μm), hence unbound, hot dust grains confined in a narrow region (~0.1 – 0.3 AU) at the sublimation rim of carbonaceous material (tip of the iceberg)
- (2) a population of bound warm grains at ~2AU that is protected from sublimation and has a higher mass despite its fainter flux level.

KIN SURVEYS STATISTICAL RESULTS

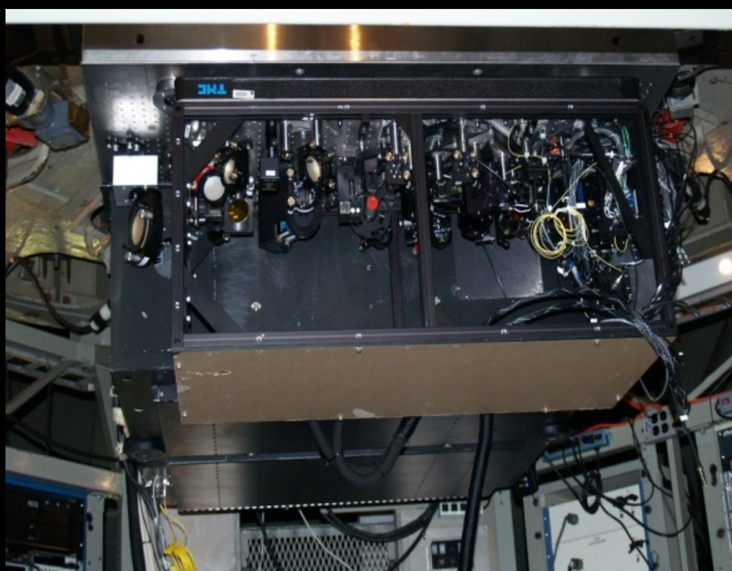


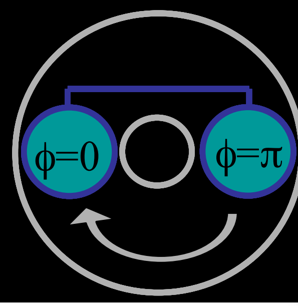


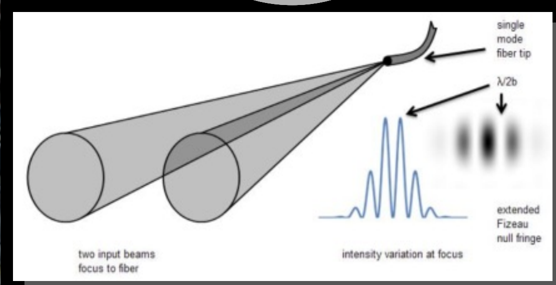


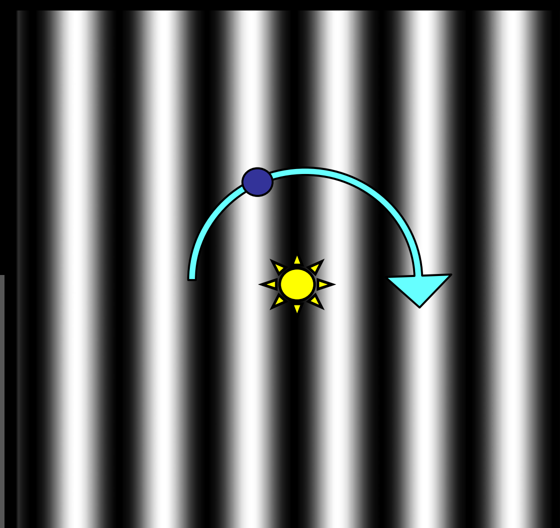
- All histograms are heavily skewed towards positive detections
- Zodi level and excess significance distributions show 8+ stars with a MIR excess detected by the KIN
- Will feed into ~10x higher accuracy LBTI survey

High contrast interferometric observations with the Palomar Fiber Nuller (PFN)

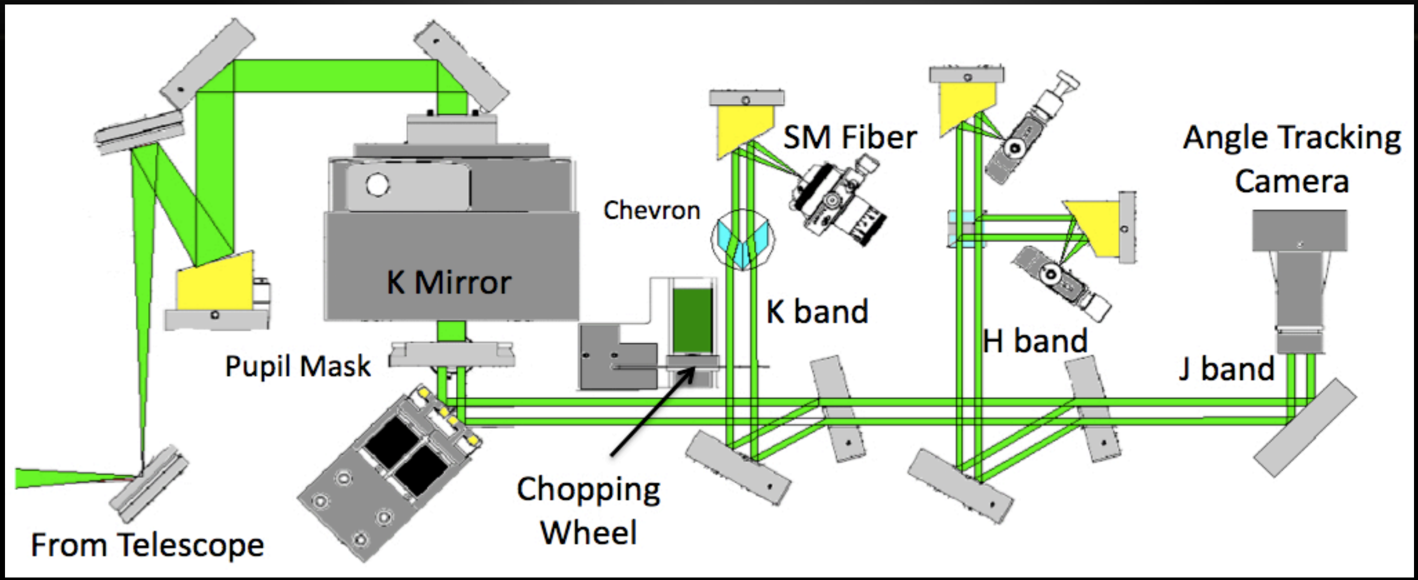






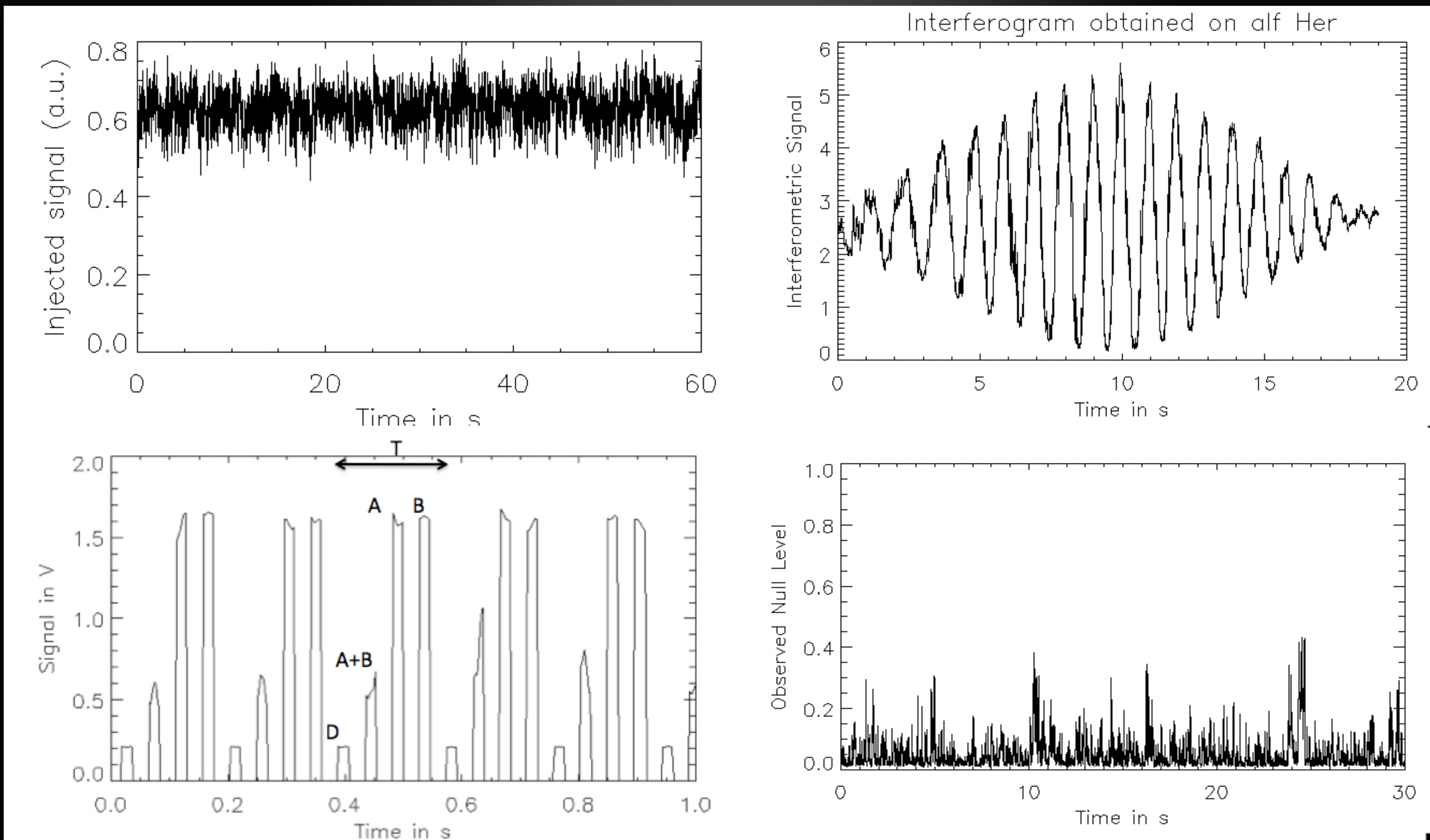


PFN Optical Set-up: a mini nulling interferometer



- Pupil Mask defines two 1.5 x 3m elliptical apertures 3.2m apart
- K mirror privides baseline rotation
- Palomar AO system stabilizes OPD (~200nm rms) and individual beam intensities
- Chopper wheel measuring interferometric, dark and individual beams every 200ms
- Both beams injected into a common IR SM fiber

PFN observing sequence: acquisition at a given baseline orientation

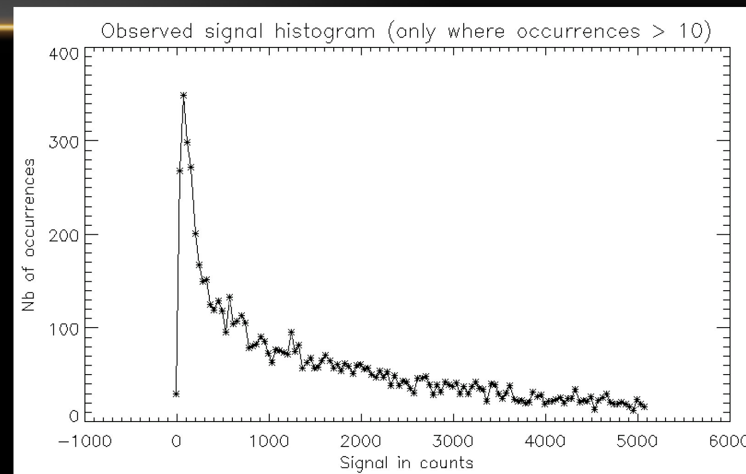


2ms sampling + beam chopping at 5-10 Hz

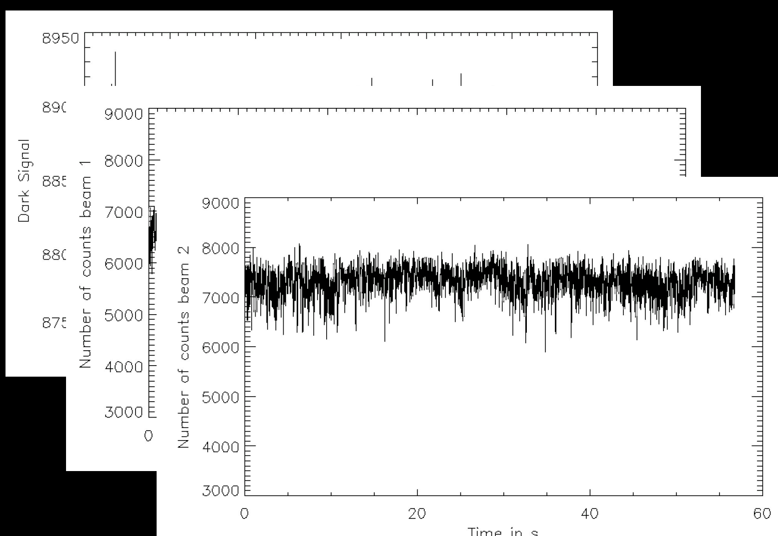
Null Sequence based on chopped data

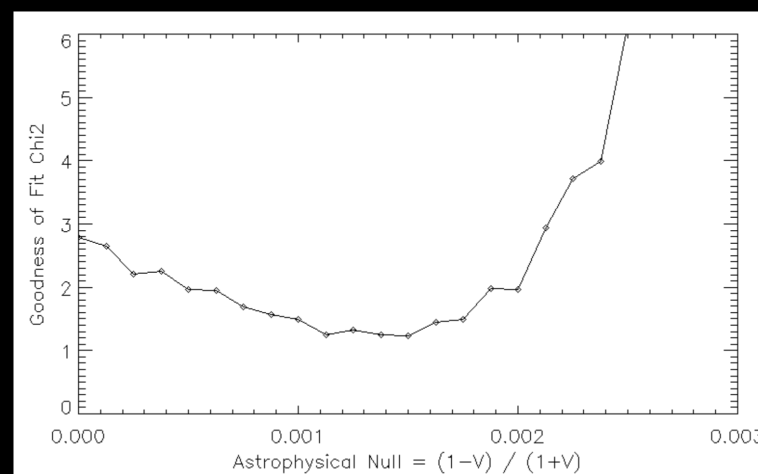
Visibility Self Calibration principle

Fringe tracked data recorded close to central dark fringe



Calibration Signals: Dark, I1, I2





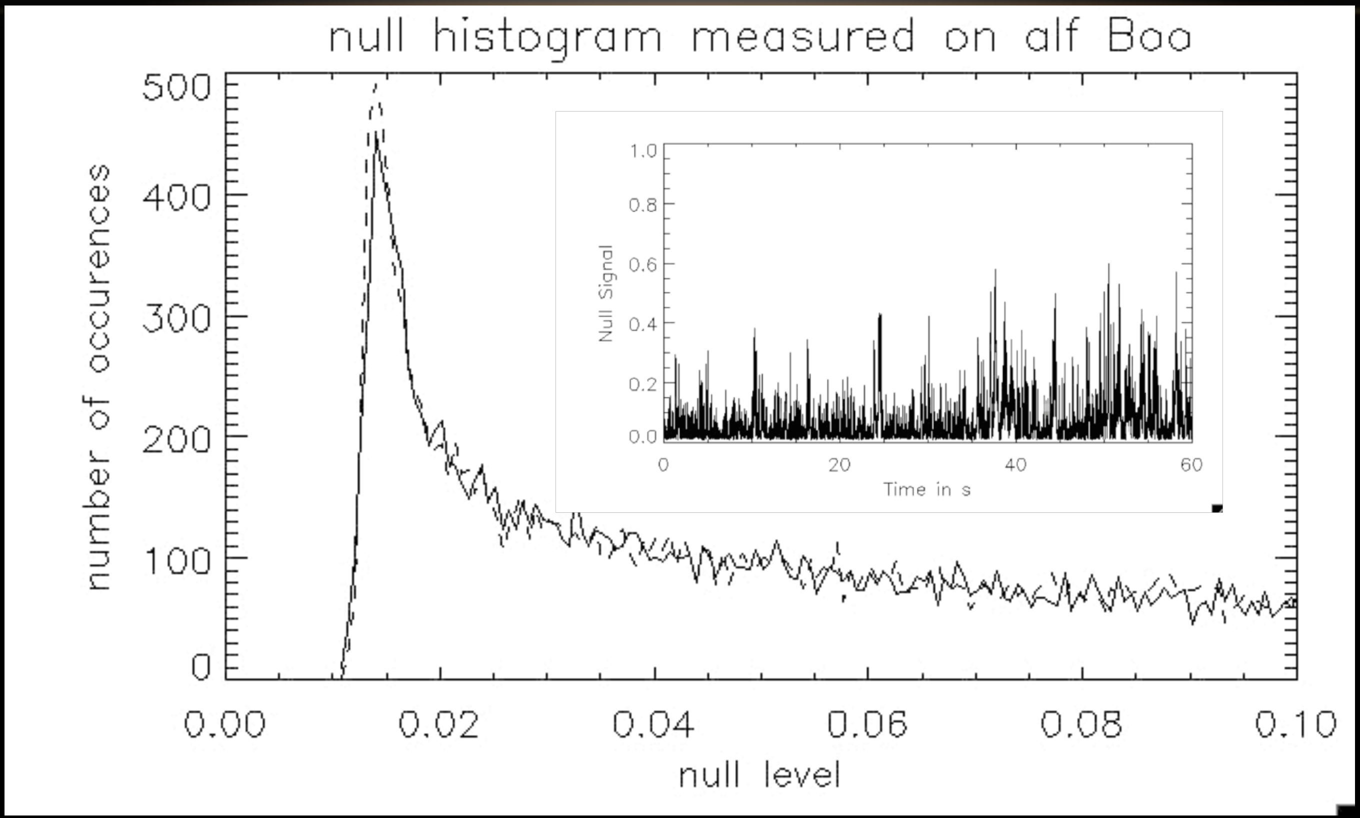
Single-mode monochromatic assumption for the interferometric signal:

$$= I_1(t) + I_2(t) + 2|V|.\sqrt{I_1(t)I_2(t)}.cos(\phi(t) + \phi_V) + D(t)$$

Null/Visibility Self Calibration Requirements

- Needs single-mode fringe tracked data (~λ/10 rms) sampled faster than coherence time
- Needs some photometric and background measurements close in time (within 1 mn)
- Needs Dispersed data if long baselines used [unless longitudinal dispersion effects are negligible e.g. LBTI common mount, single telescope NRM, vacuum delay lines]

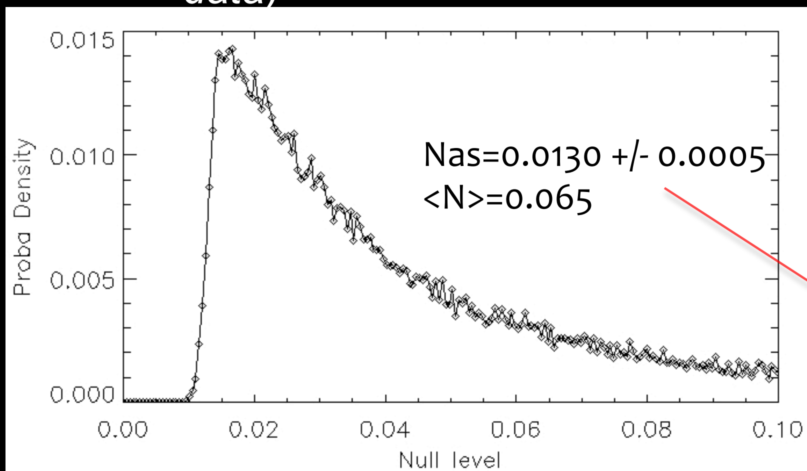
Null Distribution Fitting (Hanot, Mennesson, Martin et al. 2011, ApJ, 729, 110)



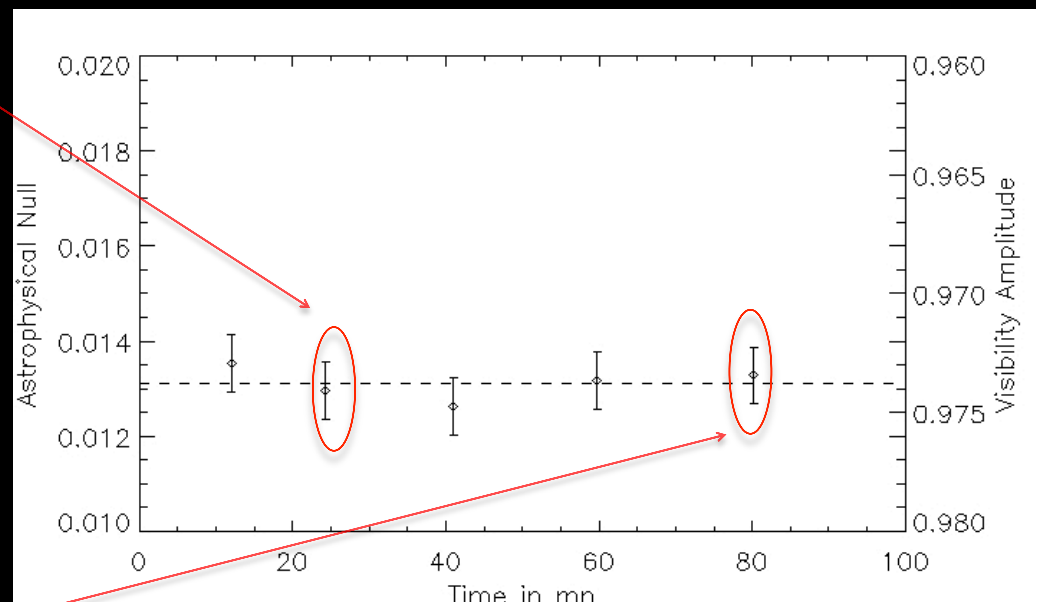
- Deconvolution of instrumental effects (piston and intensity mismatch) making use of *whole* dataset
- Can work with average nulls as bad as 10% and fluctuating by the same amount, and still measure underlying astro nulls < 0.001 with a few 10-4 accuracy
- Works as well on resolved objects, measuring accurate visibilities (tested on archival KI FT data)

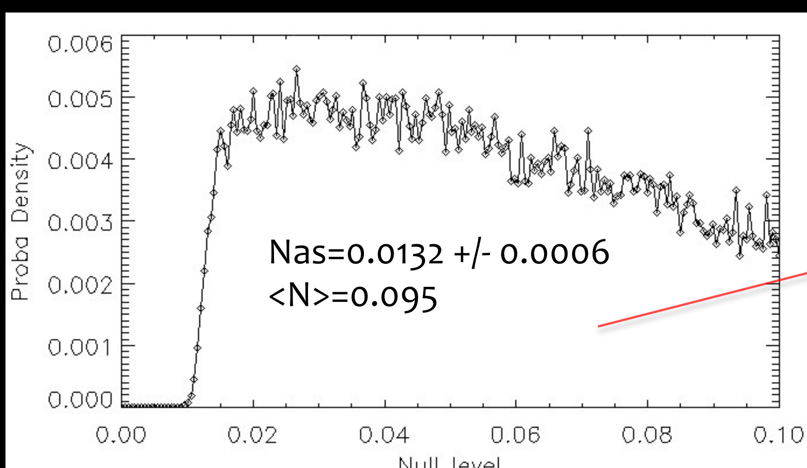
PFN Visibility Measurement Accuracy: α Boo

If N(t) = Nas + Σ quadratic terms, the average measured null (or visibility) is NOT the best observable !! The analysis of the distribution provides a much better and more robust estimator (Mennesson et al. 2011b, 2013 in prep: KI data)



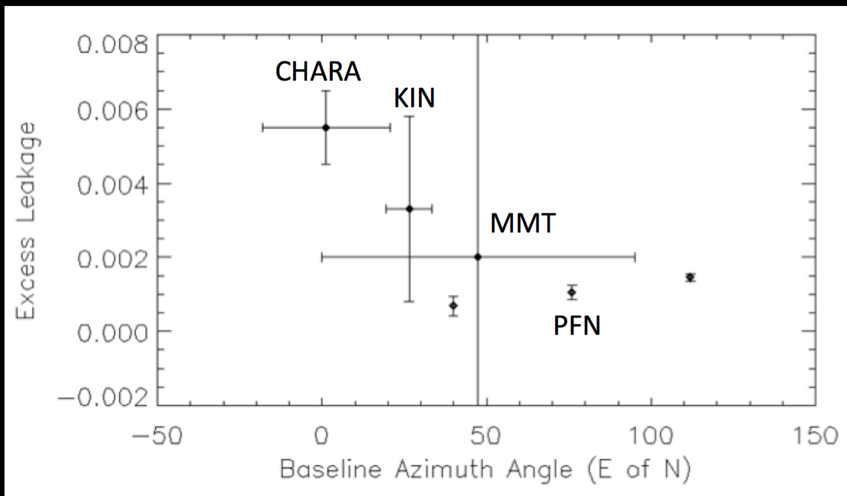
Nastro = 0.0132 +/- 0.0003
i.e.Visibility = 0.9739 +/- 0.0006

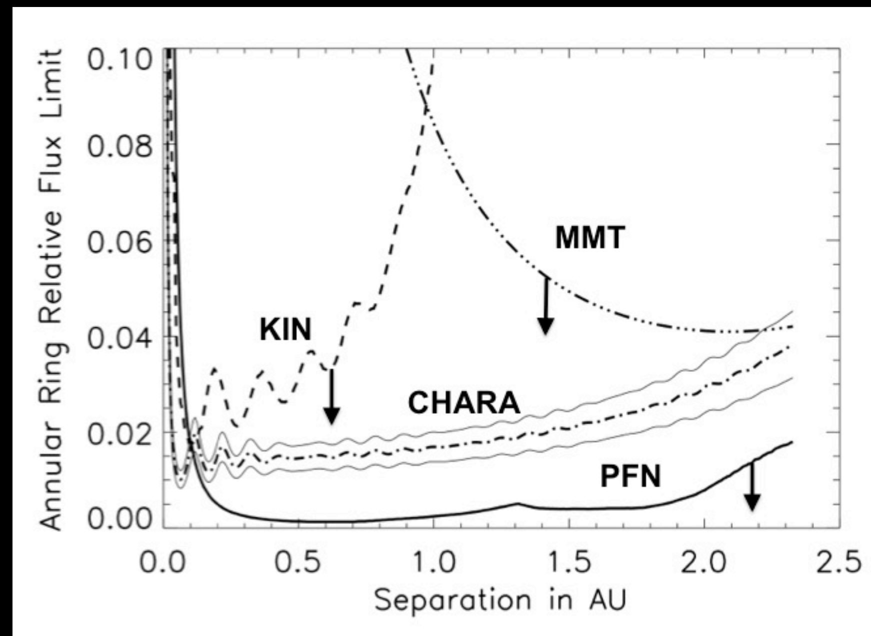




Very different instrumental conditions, but same visibility measured within a few 10^{-4}
(June 2009 Engineering run data)

HIGH CONTRAST OBSERVATIONS OF DEBRIS DISKS USING DIFFERENT INSTRUMENTS : VEGA (PFN+MMT+KIN+CHARA)





PFN measurements + KIN & MMT constraints:

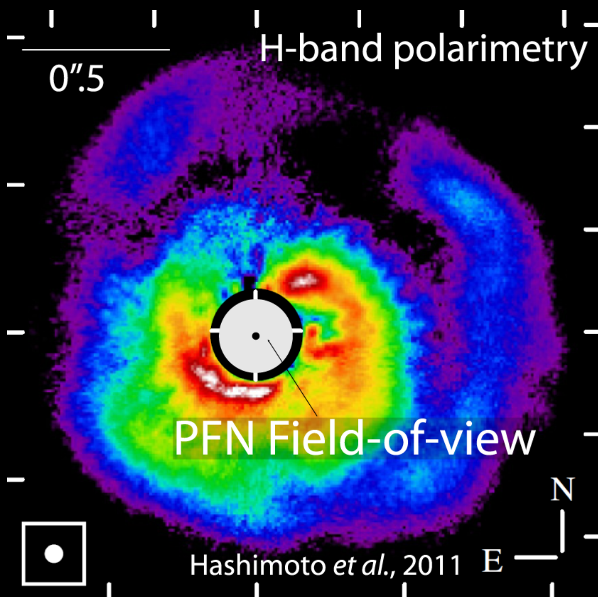
→ NIR Vega excess seen by CHARA/FLUOR and IOTA/IONIC (Defrere et al. 2011) must come from inside of 0.15 AU

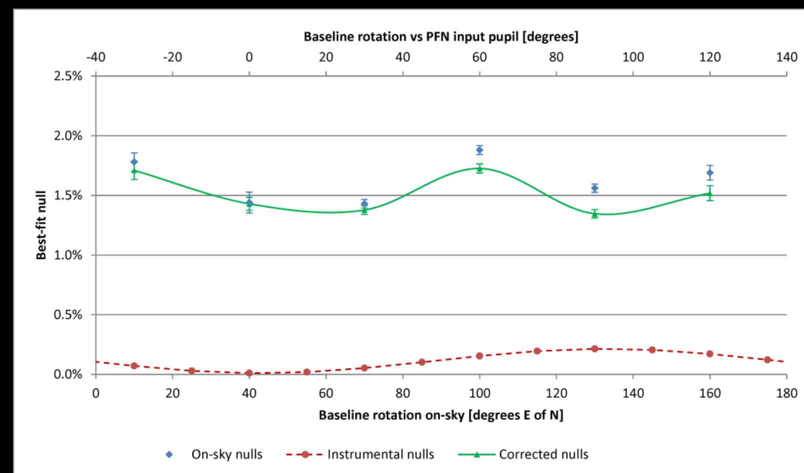
→ Not seen by KIN → very hot small grains

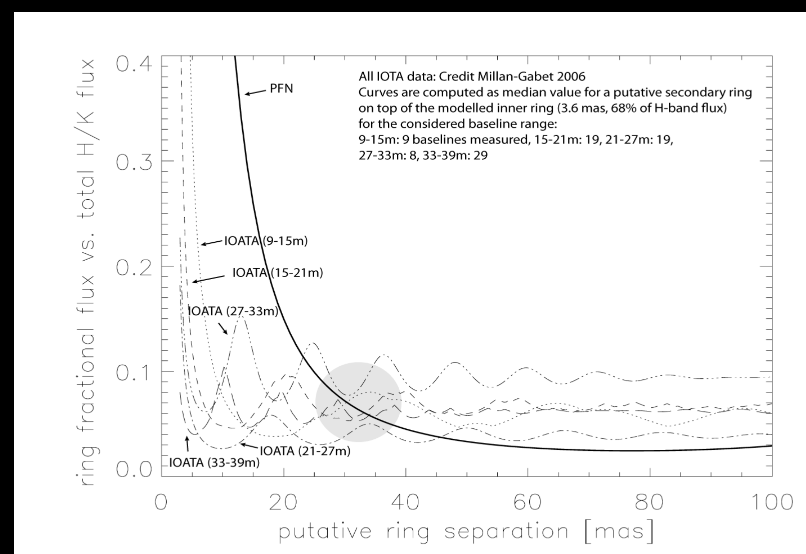
Similar to Mennesson et al. 2011, ApJ, 736, 14 but revised with new PFN data from 2012 (Vega's excess null = $3x10^{-4}$+/- 3 $x10^{-4}$, submitted to JAI as part of 2013 CHARA-NPOI conf proceedings)

[PFN observations 2011-2013: similar results on 6 FLUOR excess sources → Any NIR excess would have to come from very close-in, close to the sublimation radius]

PFN observations of AB Aur



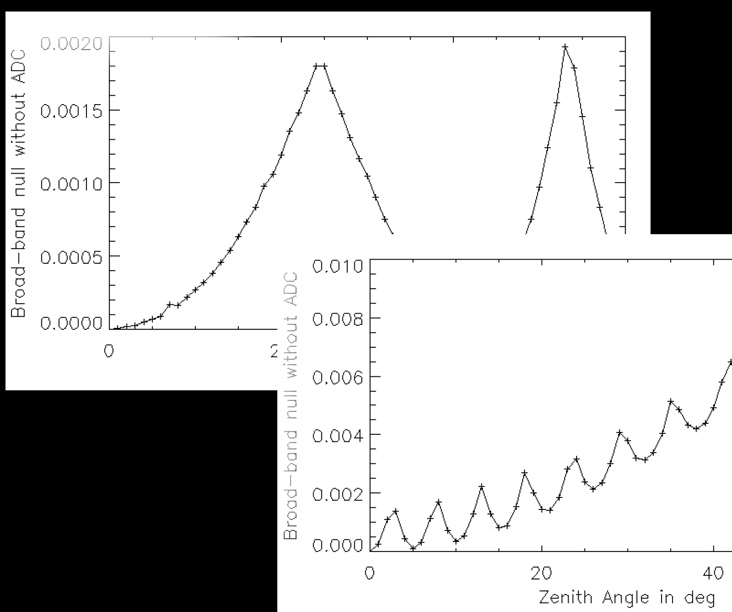


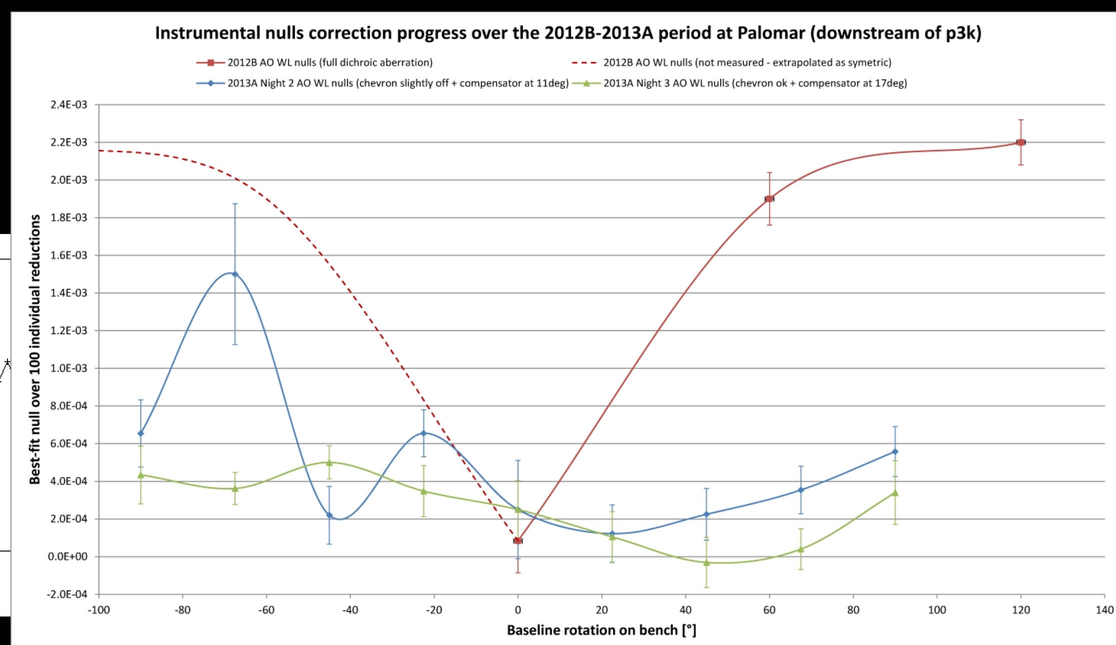


Jonas Kuhn, in prep

INSTRUMENTAL LIMITATIONS TO HIGH ACCURACY VISIBILITY AMPLITUDE MEASUREMENTS

- Dispersion Effects: Atmospheric Refraction across the band (oscillation of observed vis/null if longitudinal dispersion not actively corrected) → ADC needed or high spectral R.
- Dispersion effects: optical set-up (Palomar 200" AO dichroic !)
- Finite integration time -> residual phase jitter (depends on baseline length)
- Need for short integrations wrt τ_0 (not an issue for CP ?)
- Polarization mismatch evolution vs time





Visibility oscillation period goes as $1/(B.dn_{air}/d\lambda)$

Visibility oscillation amplitude goes as $B^2\,\Delta\lambda^2$

HIGH CONTRAST INTERFEROMETRIC STUDIES: FUTURE

- Palomar FN (K=5 → K=7, contrast > 10^3 between 30 and 200 mas)
  - Programs: planetary formation (the first 10 Myr, e.g. AB Aur resuts and a few CHARA/FLUOR hot debris disks → ends in 2014. Demonstrator for 10^4:1 contrast in the NIR.
- CHARA/FLUOR: Extension of NIR hot disk survey
  - 42 → 100 stars by 2016, K<5, 0.1% V accuracy (using VSC method on fringe tracked dispersed data)
  - Objectives: radiative transfer modeling and better understanding of dynamical aspects (how do such small grains escape radiative blow-out over long timescales?)
- CHARA/MIRC and VLTI/PIONIER
  - Any way /need to further improve CP accuracy which is already the best in the world?
- VLTI: MATISSE (L,M,N)
  - Planetary formation: Imaging of young stars and debris disks. Any possibility / need to improve currently planned CP and visibility accuracies? (dynamic range not a priority at the moment)
- LBTI Nuller Survey (N)

  Goal: survey 60 nearby MS stars down to 3 to 30 zodis level (2013- 2016) ....

  Measure background down to < 1ppm (lower than keck, multi-pixel array → 2ppm already

  Apply VSC method to measure nulls much deeper than mean null level *and* rms fluctuations
- New Ideas: CP +Nulling? (John, Mike, Sylvestre...)