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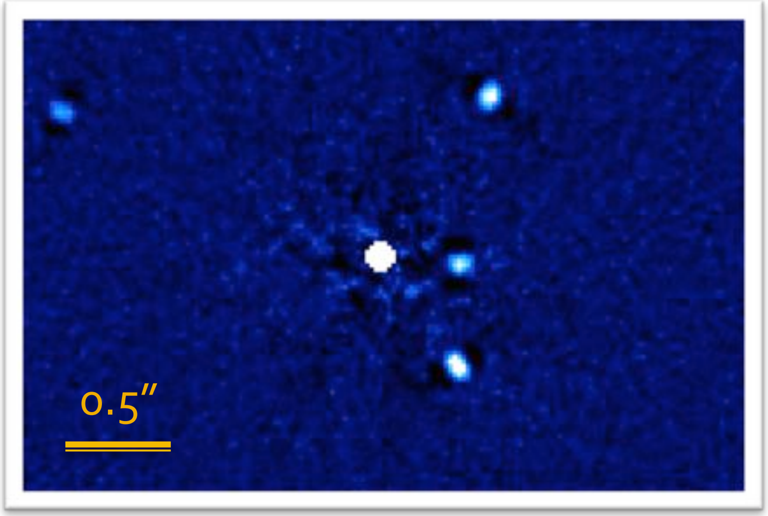
High-contrast companions: the PIONIER view

Context: the exoplanet craze

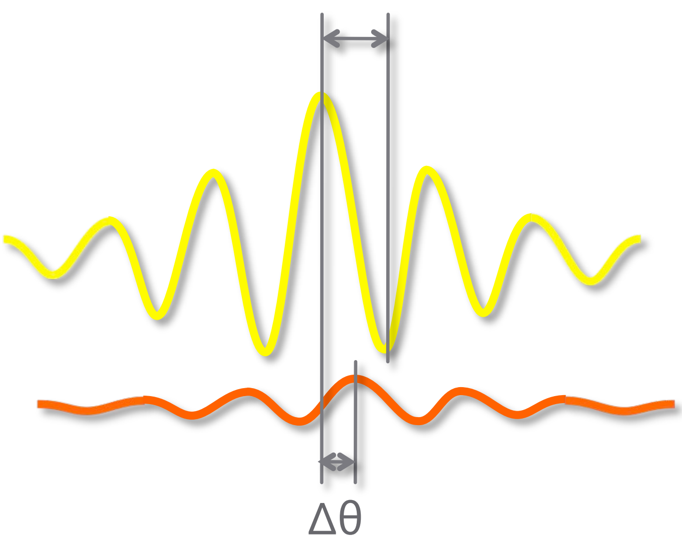
- 20+ exoplanets imaged
  - Near-IR contrast ≤ 10^{-3}
  - Separations: 0.4″ – 10+″
- Shorter separations?
  - Extreme AO: ~100 mas
    - Dynamic range ≥ 10 mag
  - Aperture masking: ~30 mas
    - Dynamic range ~ 7 mag
  - Interferometry: ~1 mas

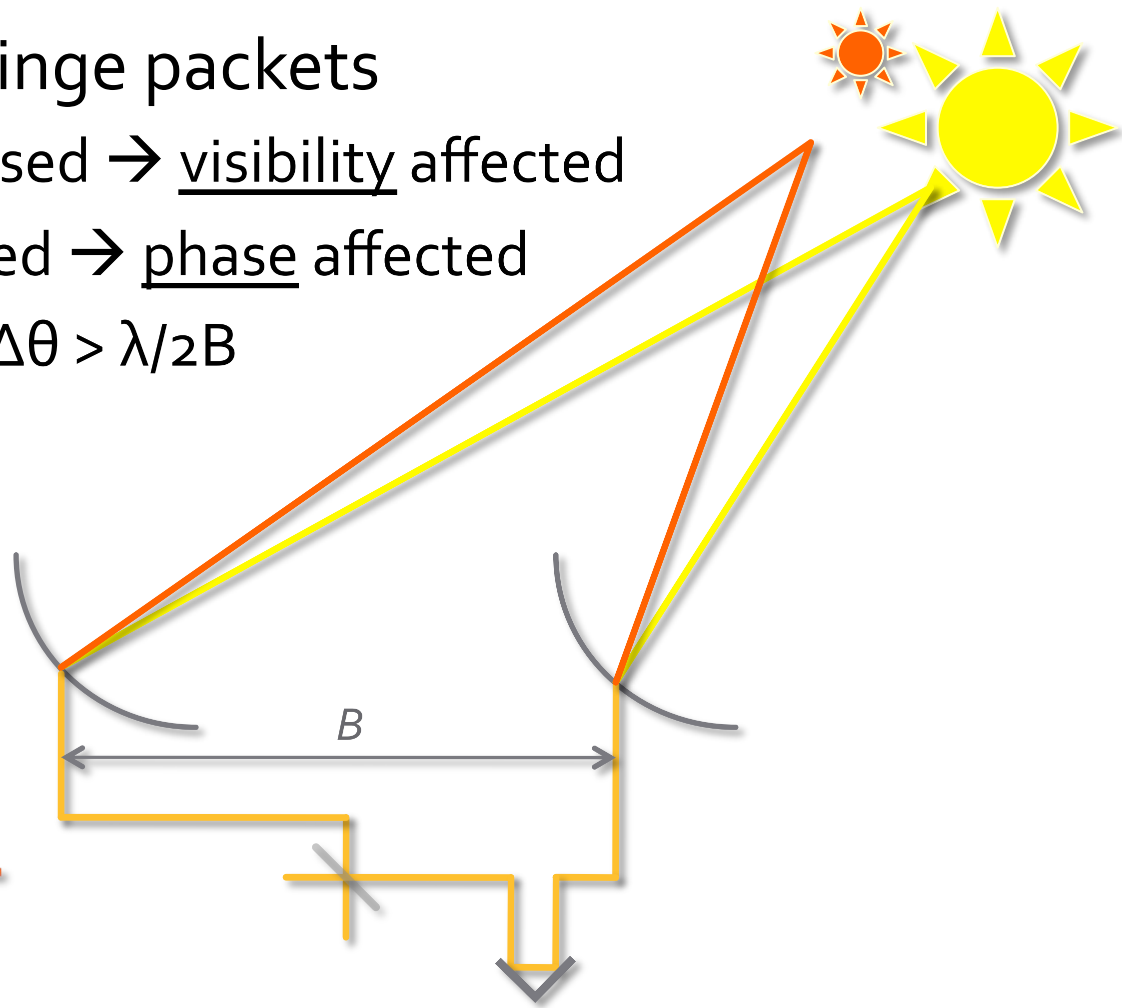


HR8799 with LBT/LMIRCam+AGPM

Interferometric view of binaries

- Sum of 2 offset fringe packets
  - Source size increased → visibility affected
  - Photocenter shifted → phase affected
  - "Resolved" when $\Delta\theta > \lambda/2B$





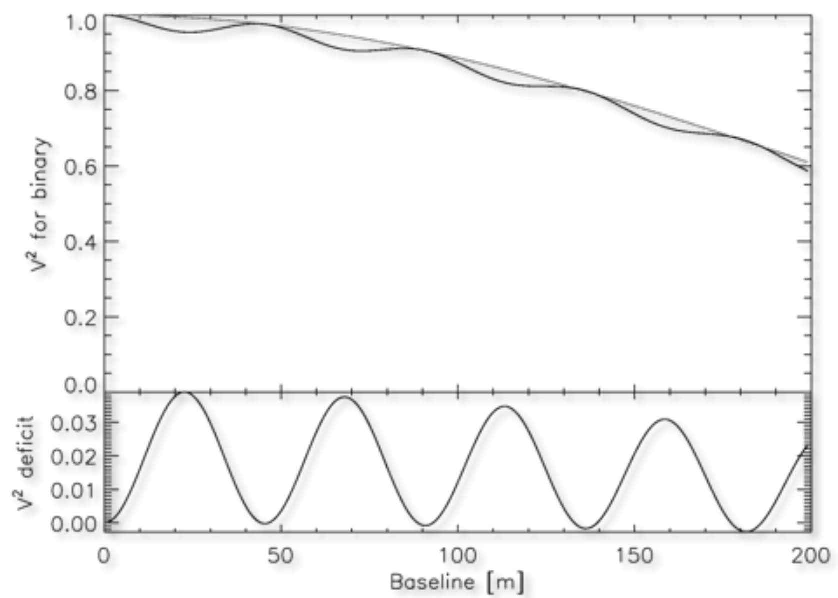
Detection methods

- Based on fringe amplitude
  - Squared visibililities
  - Nulling
- Based on fringe phase
  - Differential phase
  - Closure phase

Squared visibilities

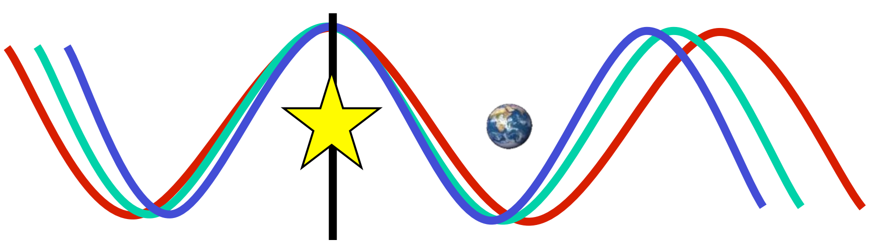
- Drop in V^2
  - Up to 4× flux ratio
  - Period $\lambda/\Delta\theta$ vs. *B*
- Robust astrometry needs many OBs
  - Or multi-telescope array
  - 180° ambiguity remains
- Dynamic range
  - ~100:1 assuming 1% accuracy on V2

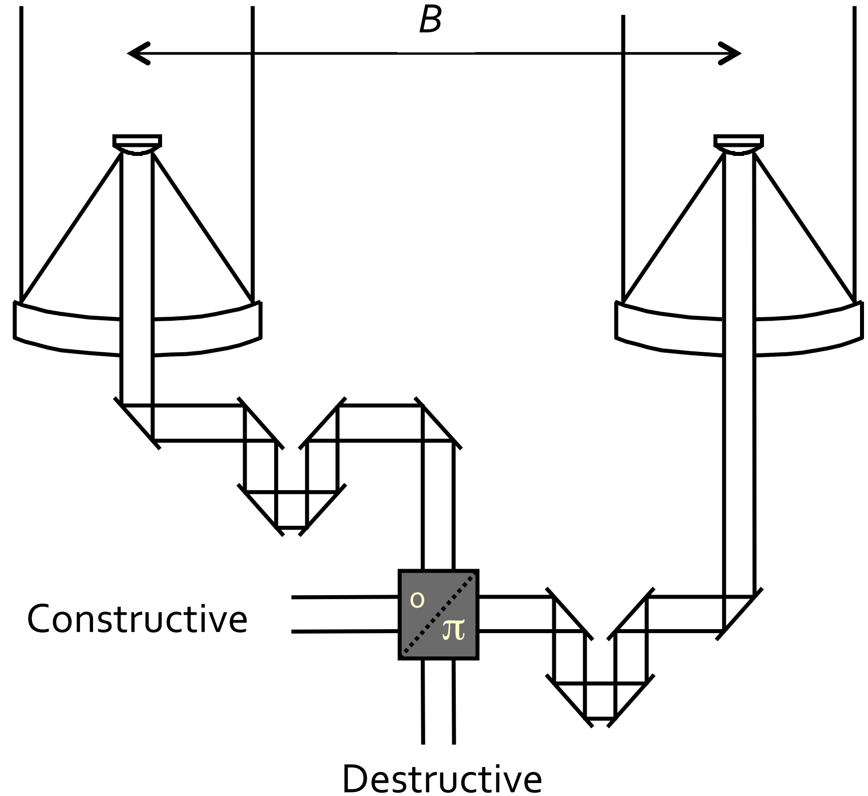
1% contrast at 10 mas

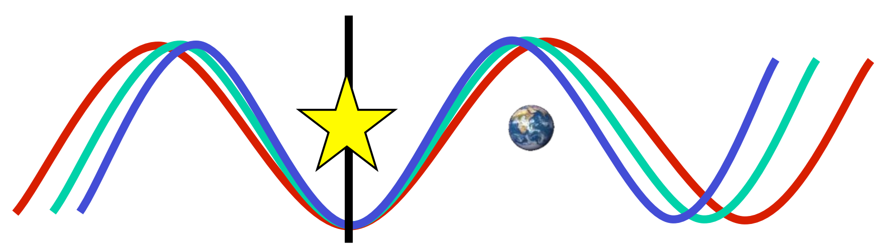


Nulling interferometry

- Put the 2 beams in phase and lock them
- Introduce achromatic π phase shift
- Dynamic range ≥ 10^3:1 (Palomar Fiber Nuller)

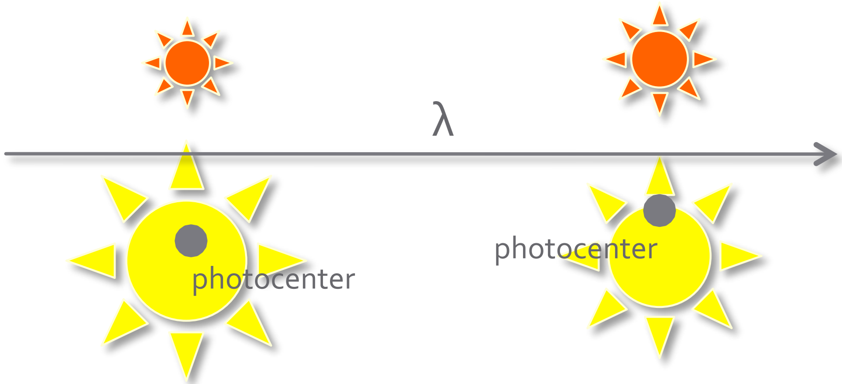


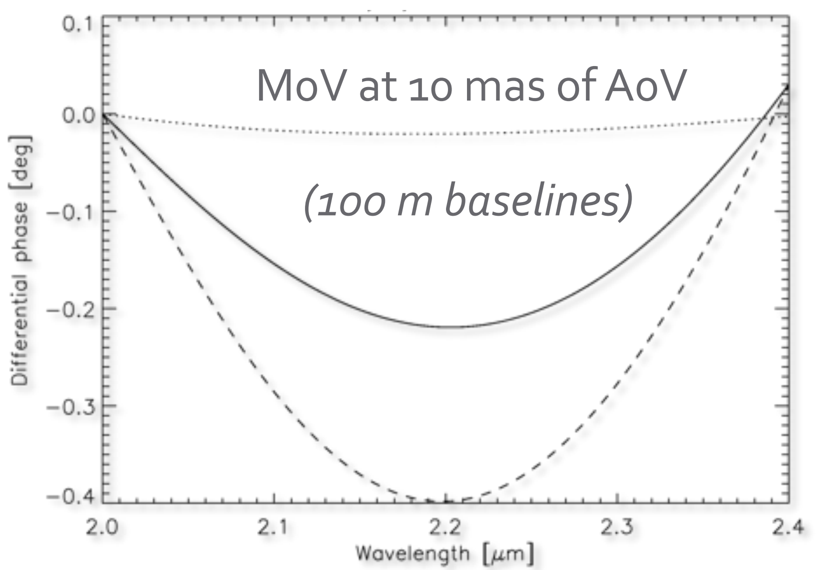




Differential phase

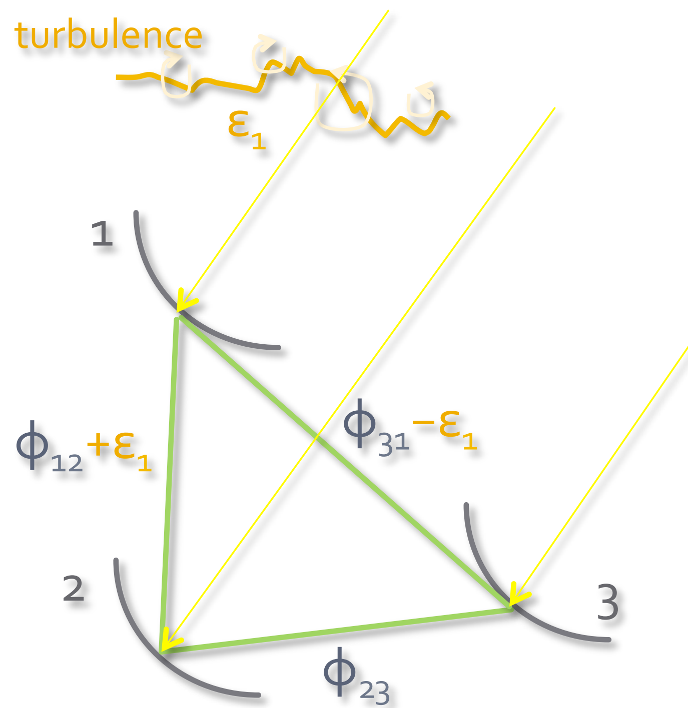
- Absolute phase lost due to turbulence
- Wavelength-differential phase can be measured
  - Non-zero if star and companion have different spectra
- Affected by dispersion
  - Contrast limited to a few 100:1





Closure phase

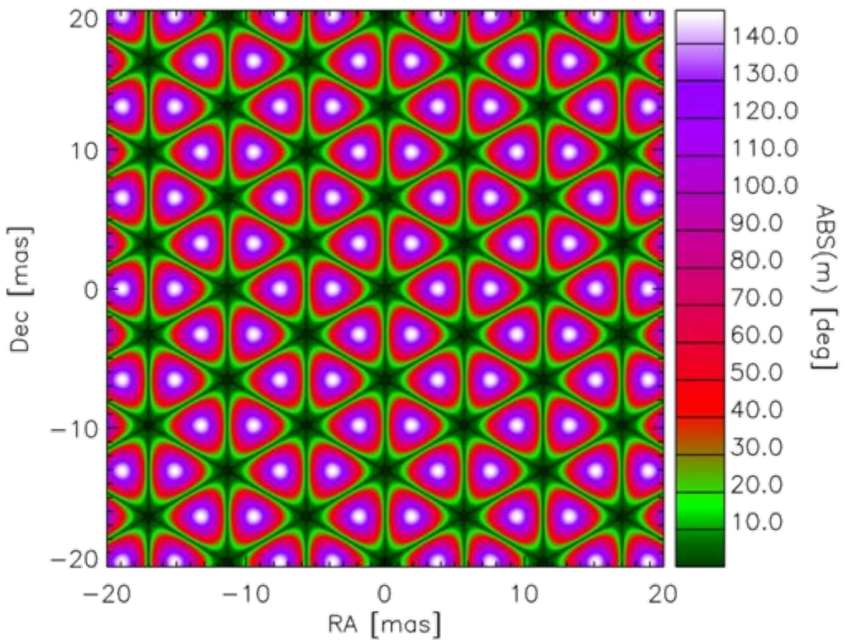
- $\Psi_{123} = \phi_{12} + \varepsilon_1 + \phi_{23} + \phi_{31} - \varepsilon_1$
  - All telescope-specific errors are removed
  - $\neq 0$ only when object not point-symmetric
- Case of a high contrast binary: $\psi = \rho m$
  - ρ: flux ratio
  - m: magnification factor
  - Primary resolved → "closure phase nulling"



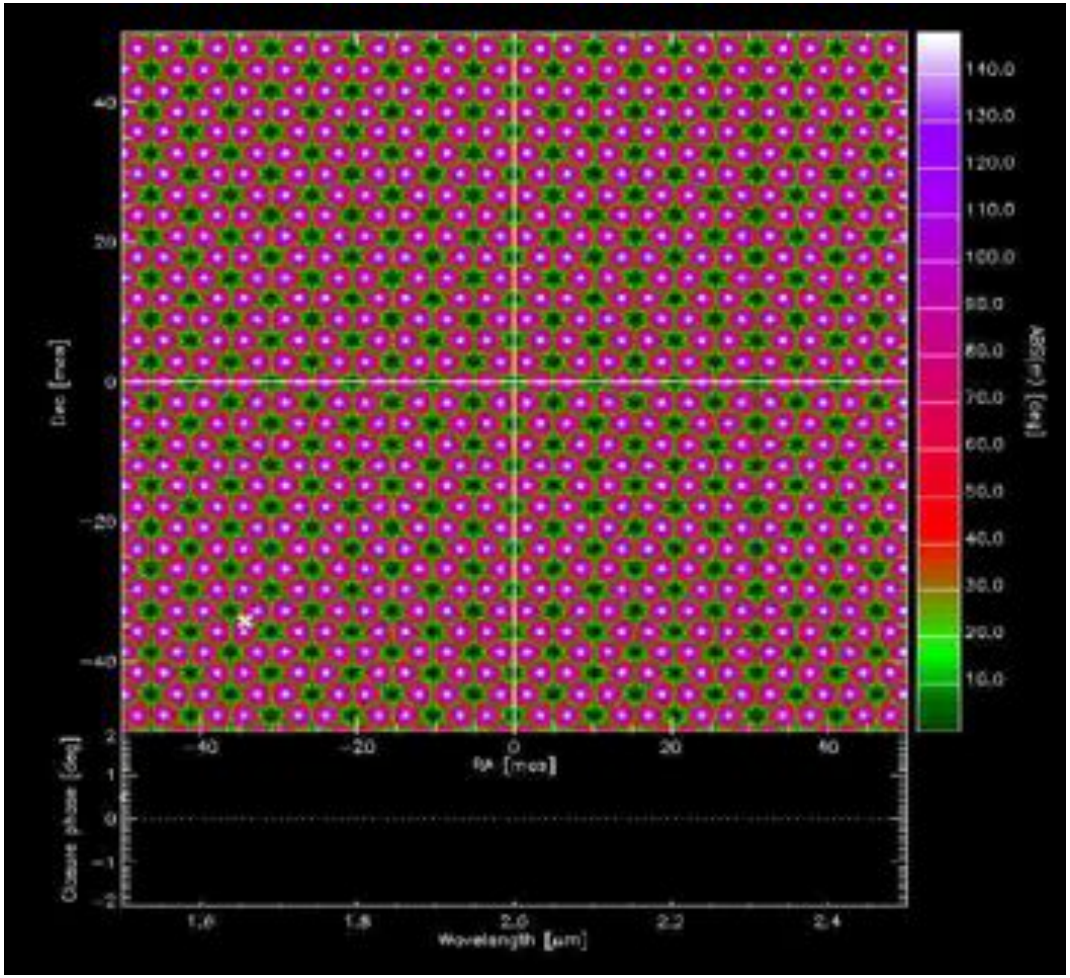
Magnification factor

- $m = \sin\alpha_{12} + \sin\alpha_{23} + \sin\alpha_{31}$
  - $\alpha_{ij} = 2\pi\, \mathbf{B}_{ij} \cdot \boldsymbol{\theta} / \lambda$
- Ranges from 0° to 149°
  - $\rho = 1\% \rightarrow \psi = \rho m \sim 1°$
- Contrast/position ambiguity solved by
  - *u,v* coverage
  - Spectral dispersion

Magnification factor “m”
(equilateral triangle, 60m baseline, H band)

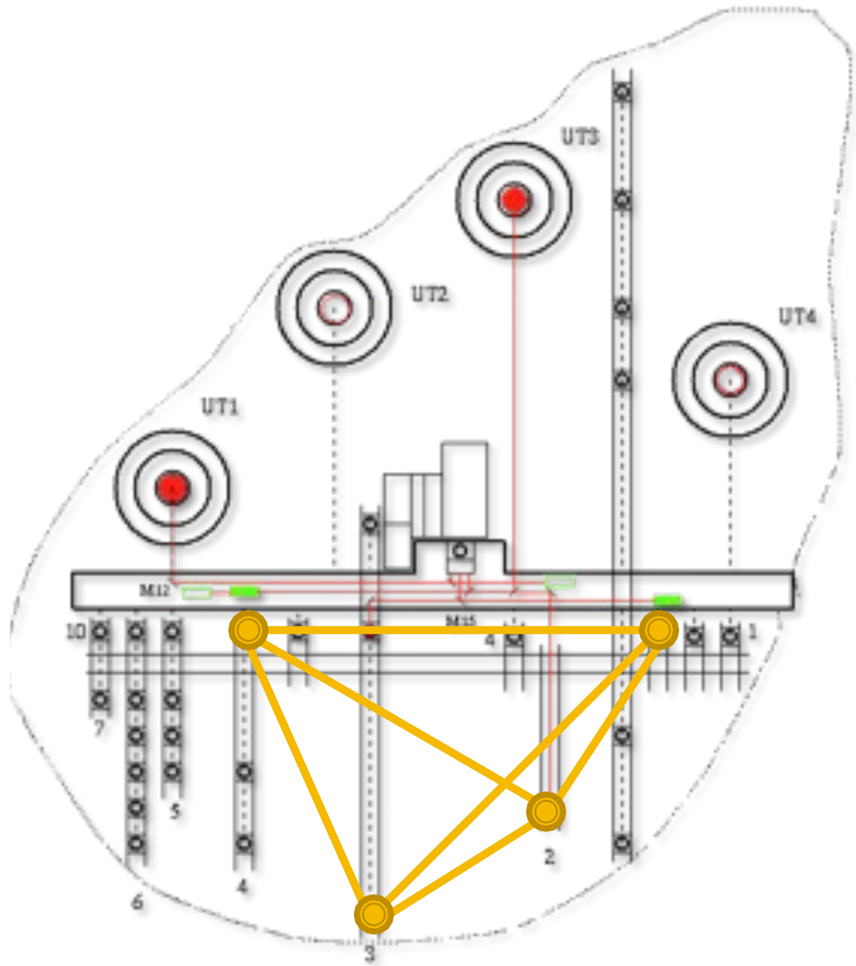


Wavelength dependence of ψ



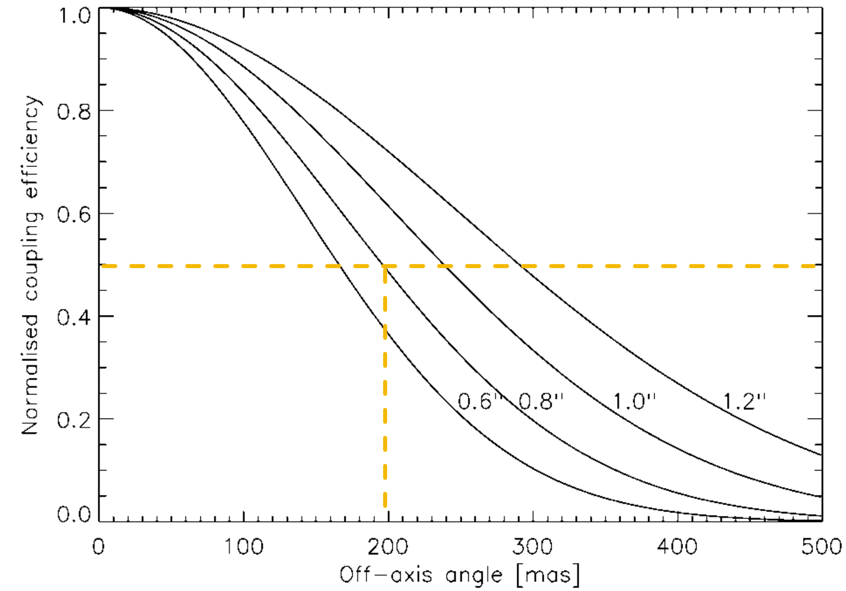
The PIONIER view

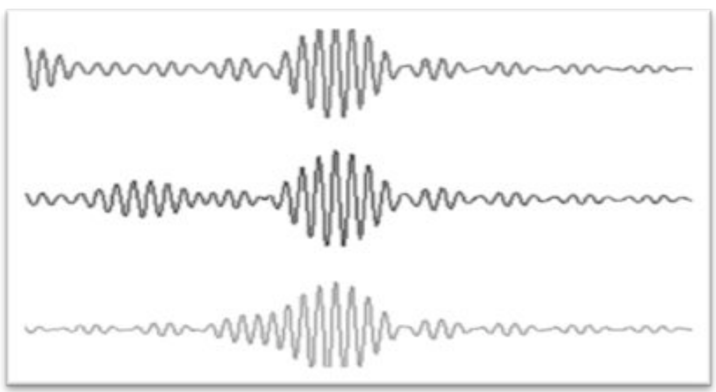
- Observables
  - 6 visibilities
  - 4 closure phases
  - Spectral dispersion
    - SMALL: 3 channels
    - LARGE: 7 channels
- Binary search tools
  - Absolute V^2
  - Absolute CP



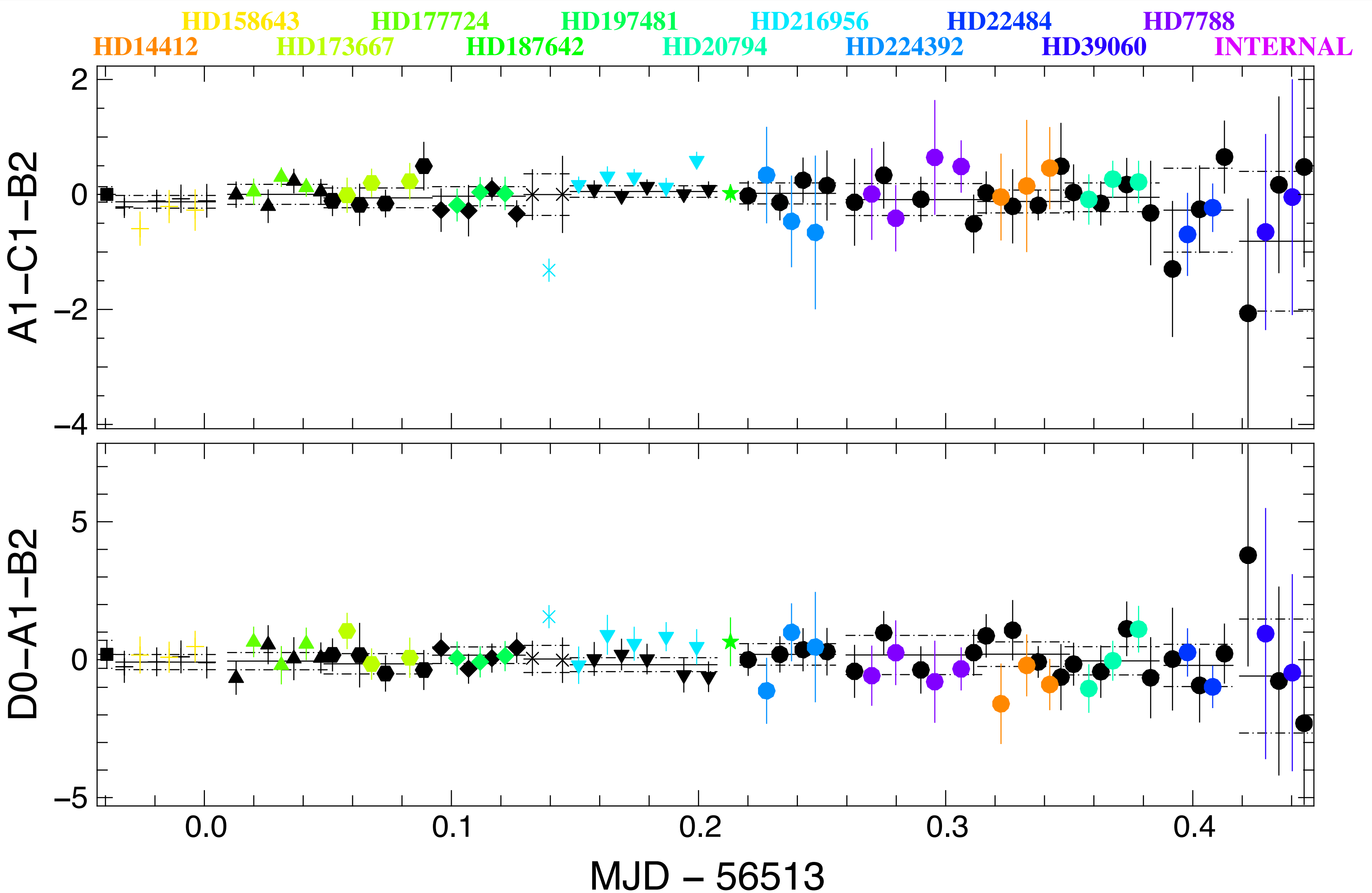
Field-of-view limitations

- Single-mode fibers
  - Injection efficiency affected by seeing
  - FHWM ~ 400 mas
- Mostly superposed fringe packets
  - 50m, LARGE → ~100 mas
- Spectral sampling
  - Period ~ $\lambda^2/B\Delta\theta > 4\Delta\lambda$
  - 50m, LARGE → ~70 mas
  - Aliasing further out





Closure phase stability



Companion search method (CP)

- Test null hypothesis (H_0 = no companion)
  - Compute χ^2 for single star model (Ψ=0)
  - Derive associated probability: $P_0 = 1 - CDF_\nu(\chi^2)$
    - CDF_ν = χ^2 cumulative probability distribution with ν dof
  - If $P_0 < 0.27\%$ (3σ Gaussian) then H_0 rejected
- Underlying assumptions
  - Gaussian noise
  - Error bars properly estimated
- In practice: χ^2/ν generally $\neq 1$ for single star

Companion search method (CP)

- Better idea (?)
  - Compare $\chi^2(0)$ with χ^2 of binary models
  - Test many binary models → χ^2 cube
- Check if adding companion reduces significantly the χ^2
  - Find χ^2_{min} in cube
  - Renormalise: χ^2/χ^2_{min}
  - Check null hypothesis

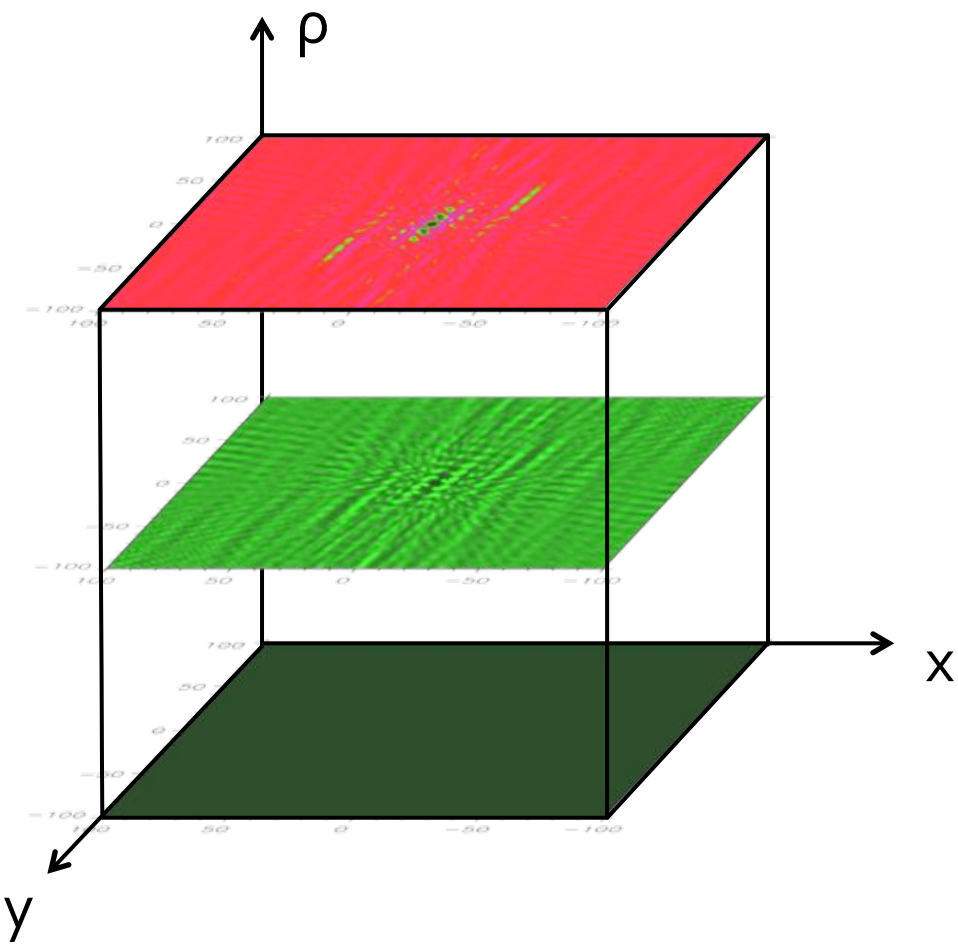
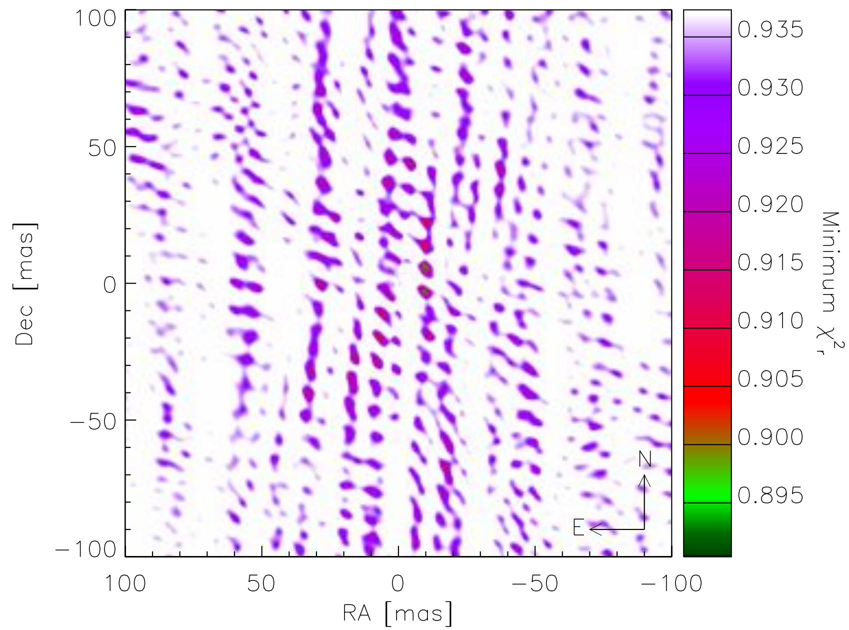
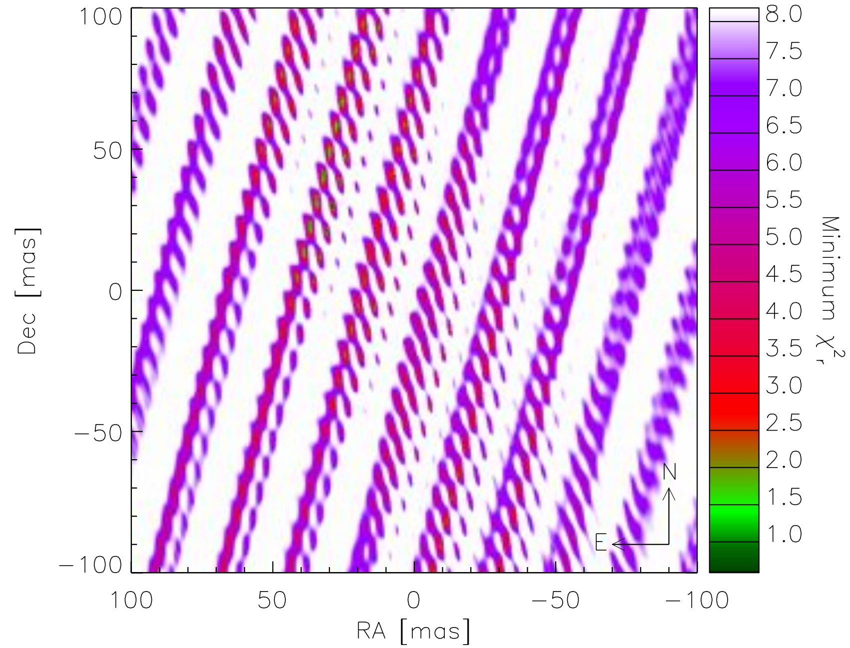


Illustration: minimum χ^2 map

NON-DETECTION



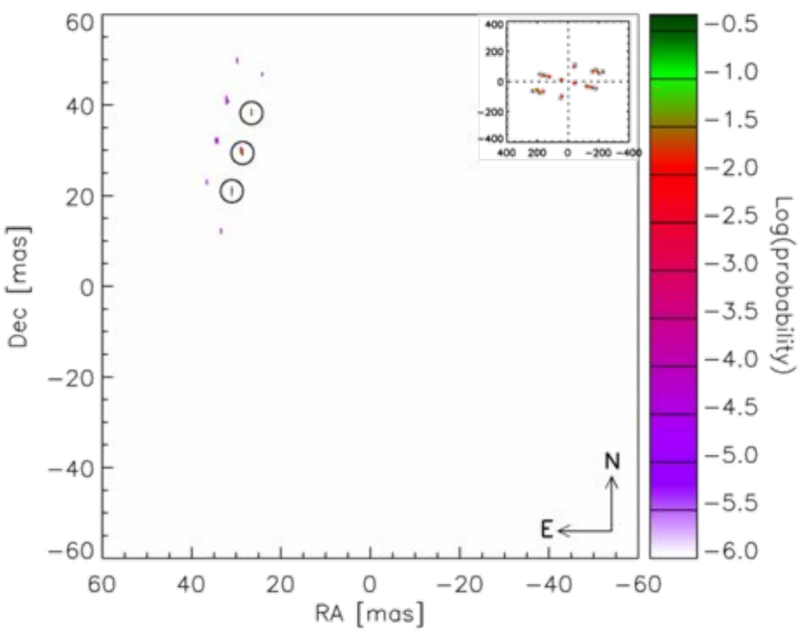
DETECTION

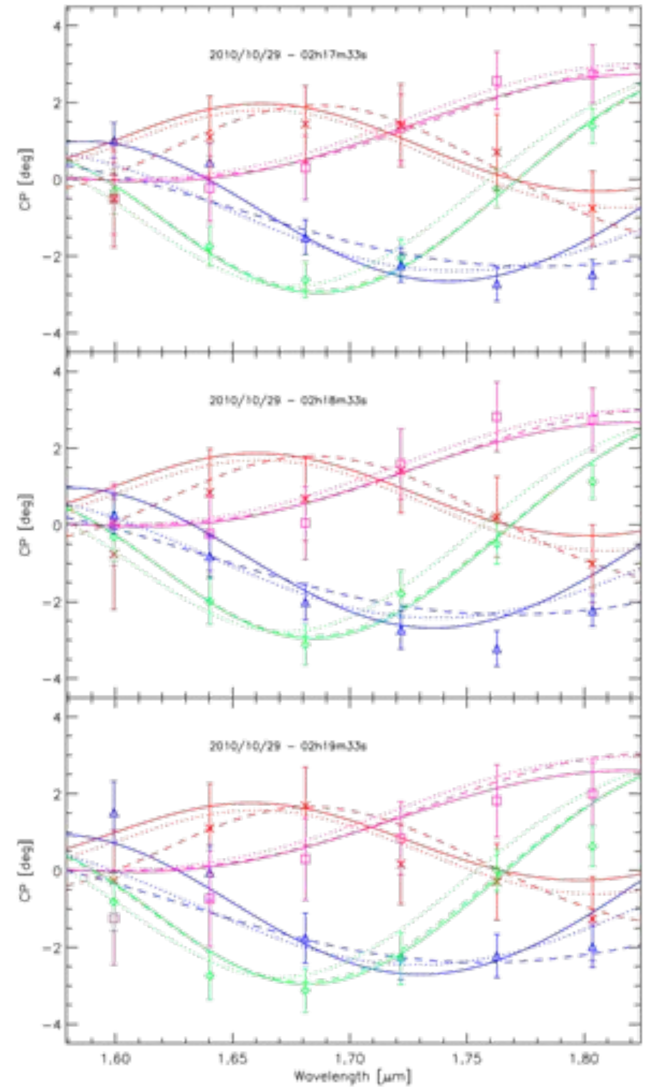


Absil et al. 2011

A companion to δ Aqr

- Long period RV + astrometry
- Contrast 2.05% ± 0.16%
  - A3V + G5V system
- Position ambiguous

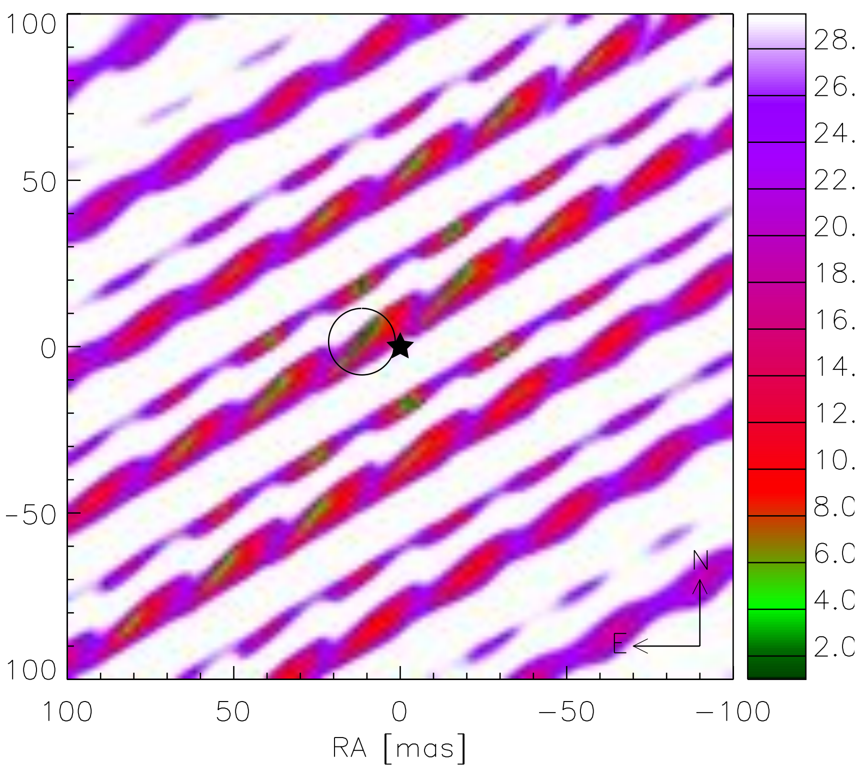




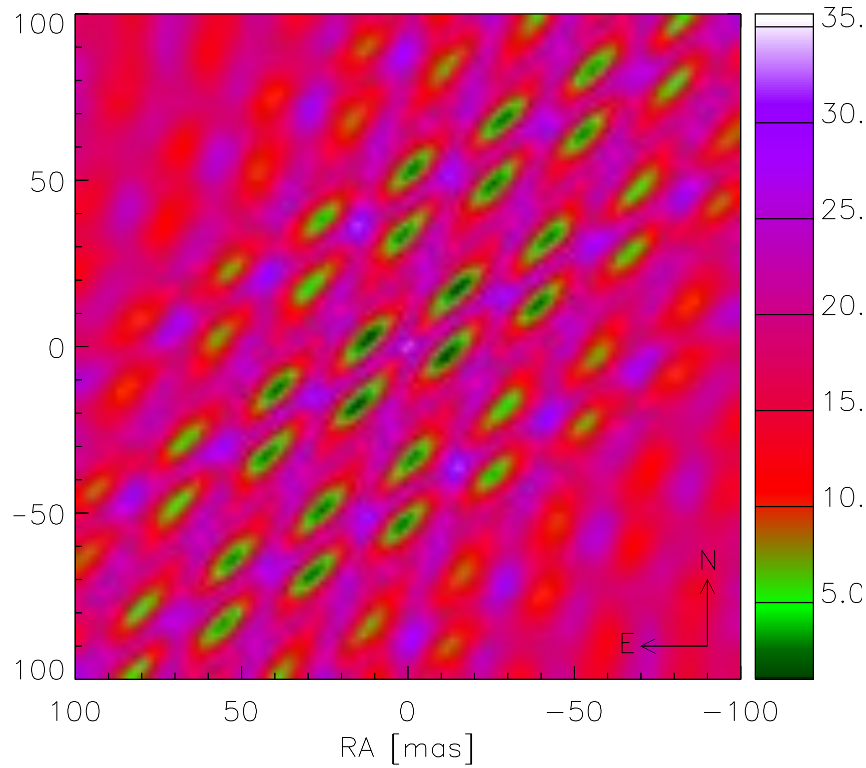
Marion et al., in prep

A companion to 90 Tau

CLOSURE PHASES

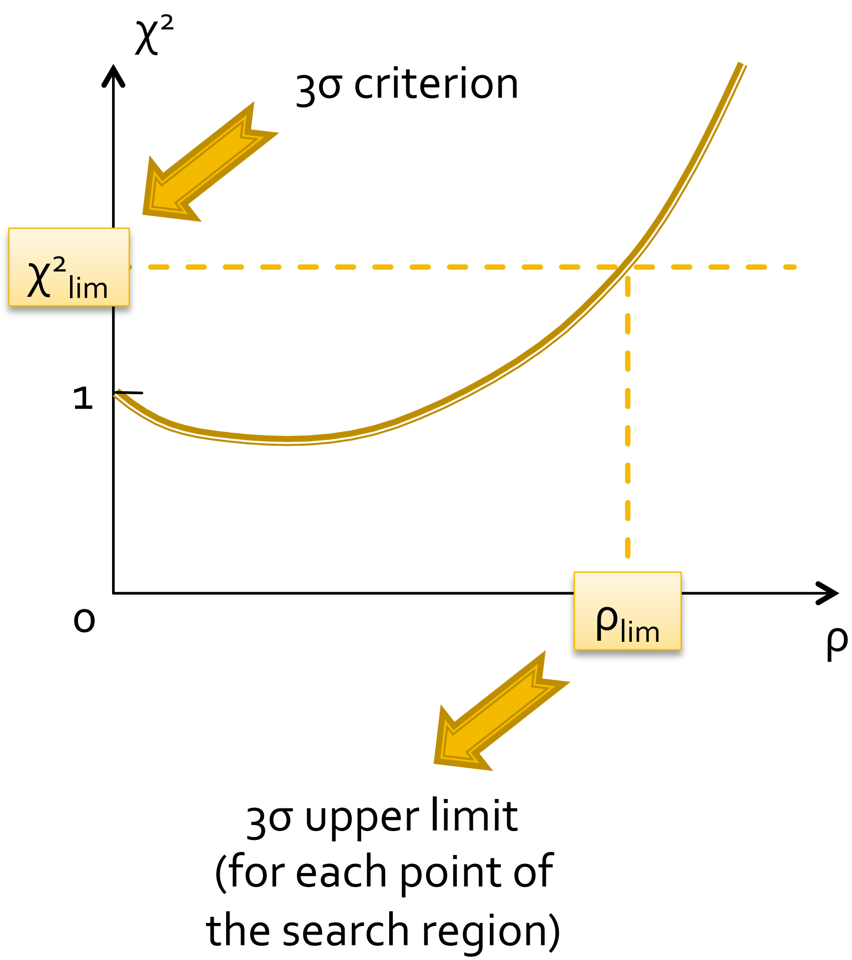


VISIBILITIES



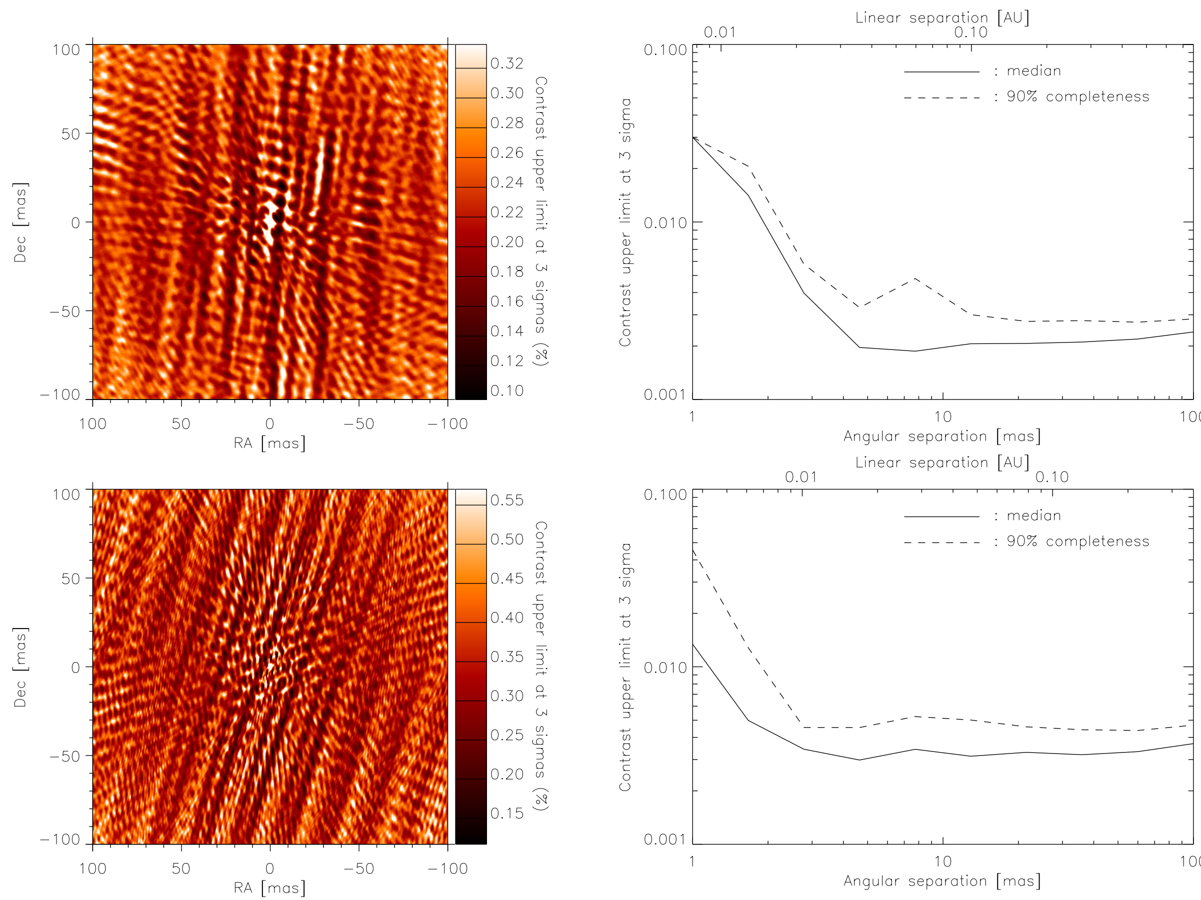
Deriving upper limits

- Based on χ^2 cube
  - Renormalise $\chi^2|_{\rho=0} = 1$
  - Find ρ such that $\chi^2 = \chi^2_{lim}$ (3σ criterion)
- Double blind test
  - Fake companions inserted into calibrated ψ data
  - Count the fraction of good detections vs ρ



Deep search: χ^2 cube

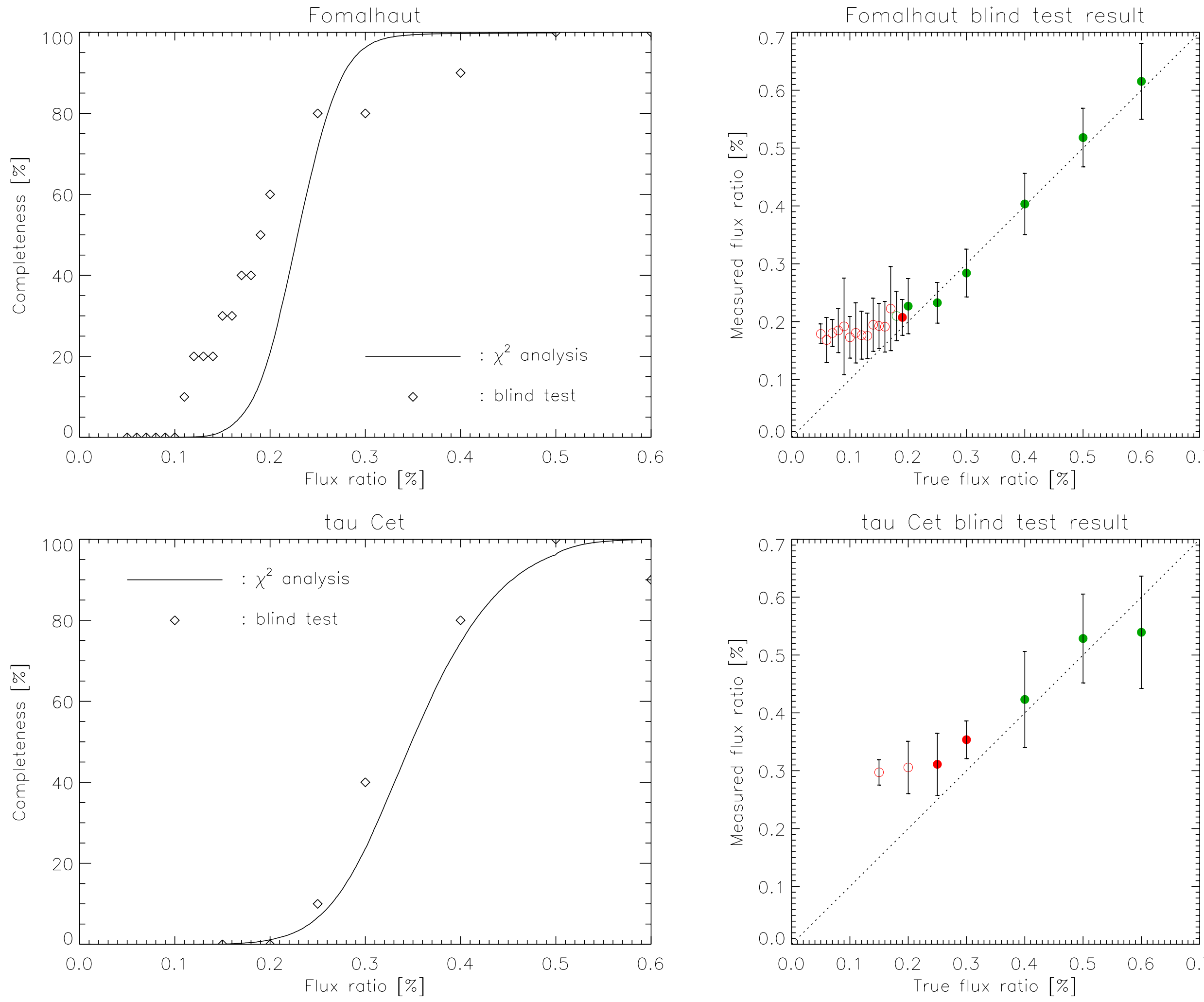
- 3σ sensitivity on 100 mas region
  - Fom: 2.3×10^{-3}
  - τ Cet: 3.5×10^{-3}
- 90% upper limit
  - $0.17\ M_{sun}$ (~M6V)
  - $0.09\ M_{sun}$ (~BD)
- Exclude companion as source of near-infrared excess



Absil et al. 2011

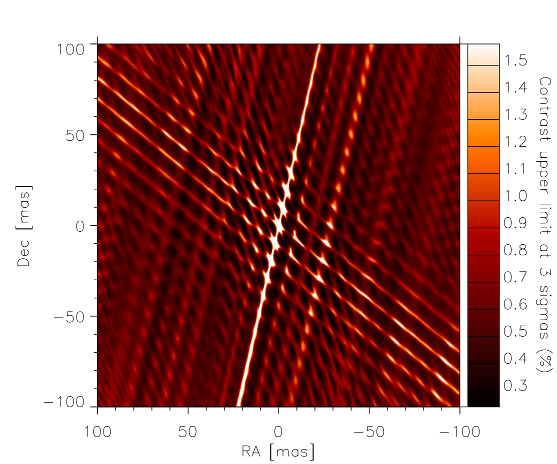
Deep search: blind test

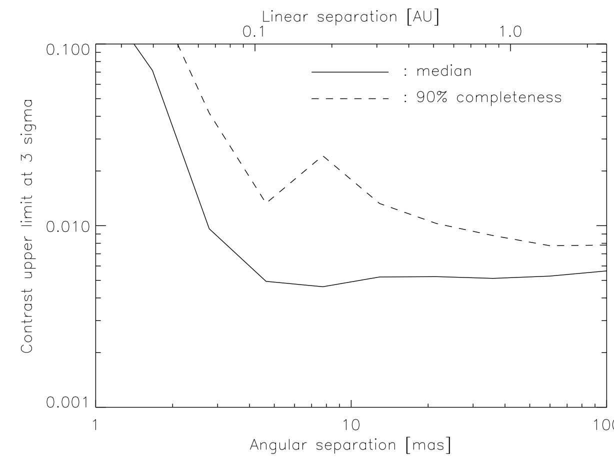
- Confirms the χ^2 results
- Median sensitivity
  - Fom: 1.9×10^{-3}
  - τ Cet: 3.2×10^{-3}
- Noise floor
  - $\leq 2.3 \times 10^{-3}$
  - $\leq 3.5 \times 10^{-3}$

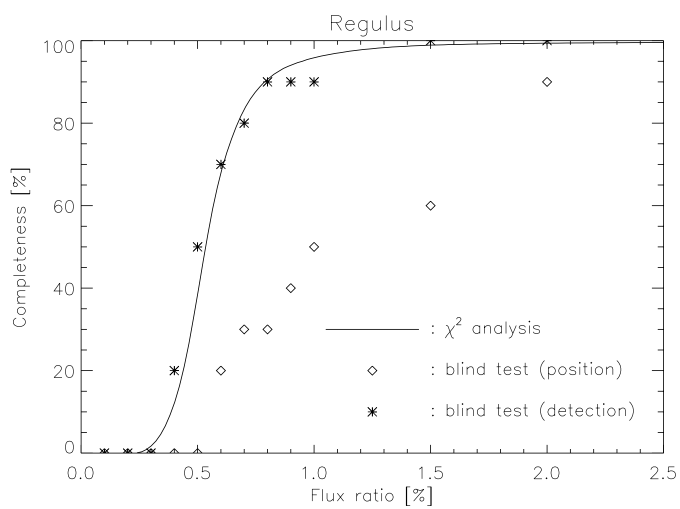


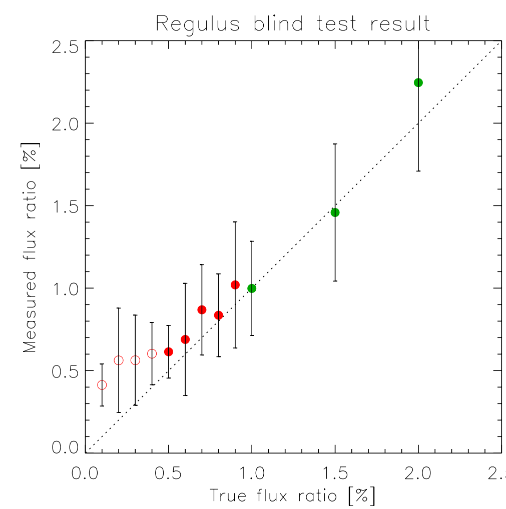
Snapshot sensitivity (Regulus)

- Median sensitivity: 5.4×10^{-3}
- Poor uv plane coverage → zones with low sensitivity
- Blind test ok for contrast but not for position
  - "Side lobes" of instrument PSF





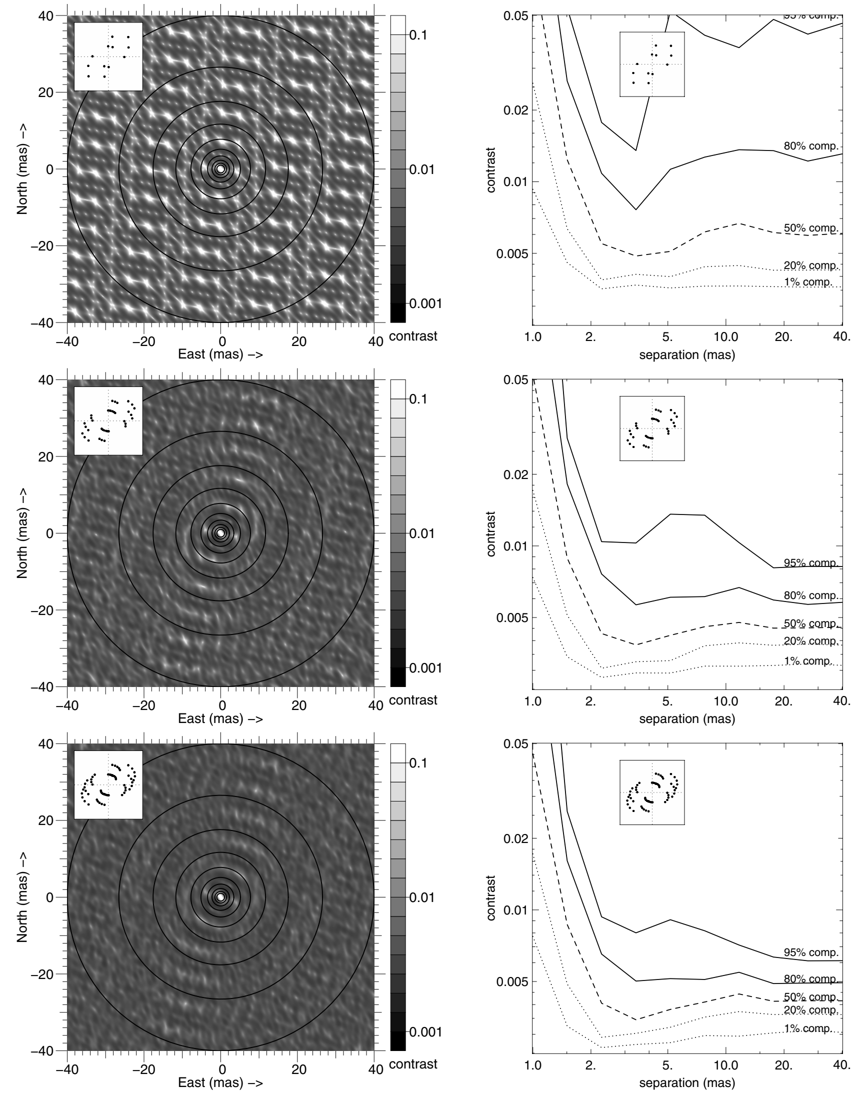




Le Bouquin & Absil 2012

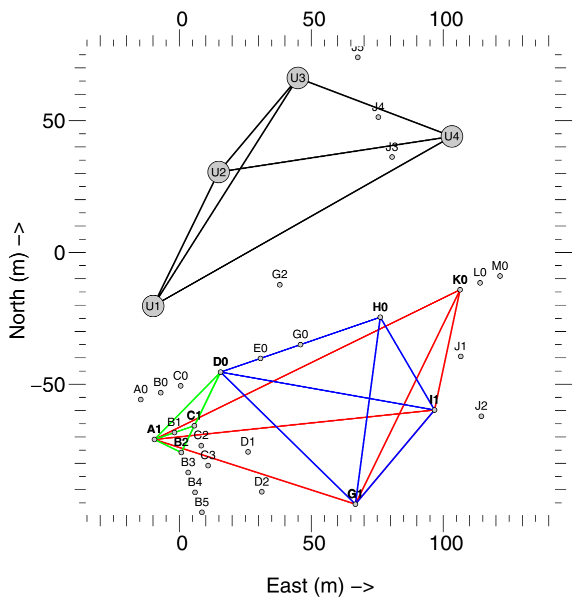
Sensitivity vs number of OBs

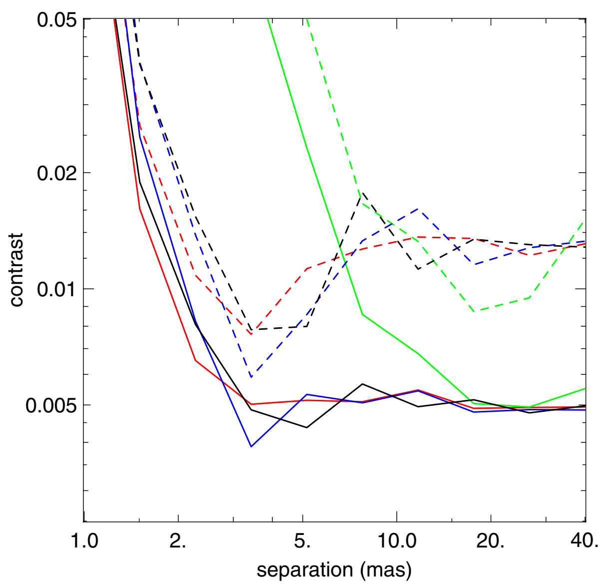
- Assume accuracy of 0.25° on A1-G1-I1-K0
- Pointings at hour angles
  - 0h
  - -1h, 0h, 1h
  - -2h, -1h, 0h, 1h, 2h
- Median sensitivities
  - $6{\times}10^{-3}$, $4.5{\times}10^{-3}$, $4.0{\times}10^{-3}$
  - Huge improvement in completeness
- 3 pointings ok for survey

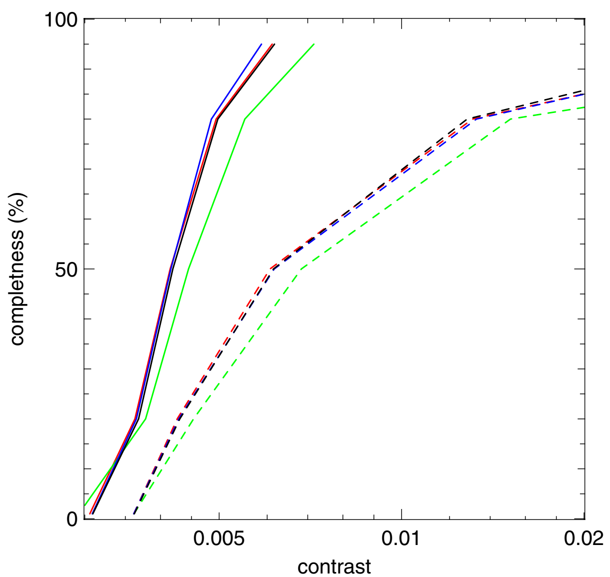


Sensitivity vs configuration

- Sensitivity does not depend on configuration
- Configuration size still matters
  - Sets inner working angle and FOV size
- Ideal filler program







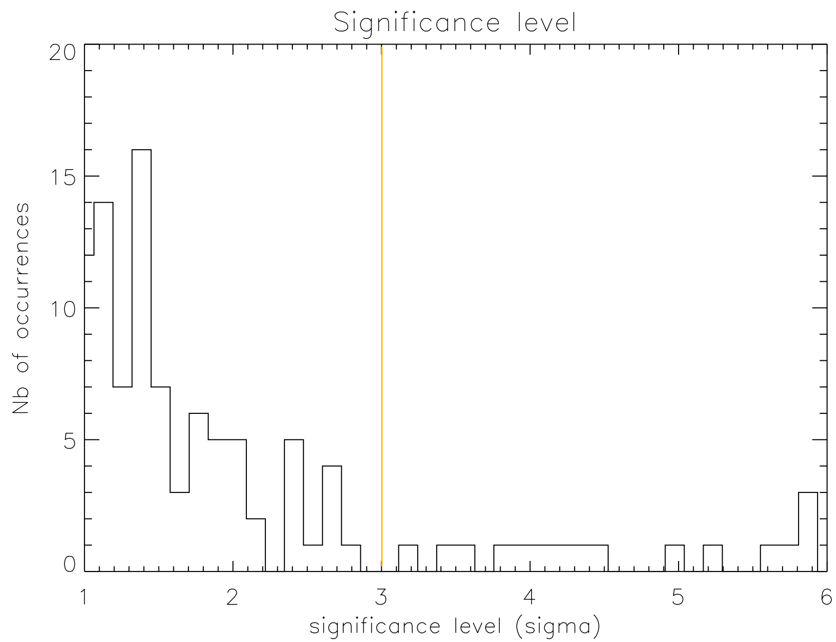
Astrophysical applications

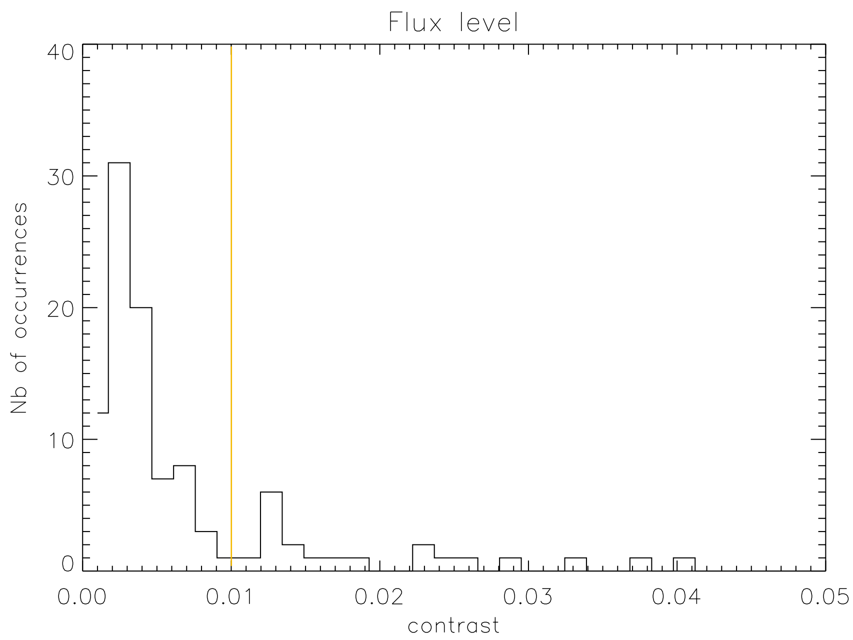
- Performance summary
  - Noise floor ~ 0.2°
  - Dynamic range ΔH~6
  - Valid up to H~6 (?)
- Warm BD/planets
  - Transition objects
  - Moving groups
  - Hot Jupiters … not yet
- Binary fraction of massive stars

Age	A0V	G0V	M0V
10 Myr	0.09 M_{sun}	0.017 M_{sun}	0.012 M_{sun}
50 Myr	0.22 M_{sun}	0.043 M_{sun}	0.013 M_{sun}
200 Myr	0.35 M_{sun}	0.08 M_{sun}	0.030 M_{sun}

Example: the EXOZODI survey

- ~90 stars in H band
- ~20 stars in K band (some overlap)
- Use combined χ^2 for V^2 and CP



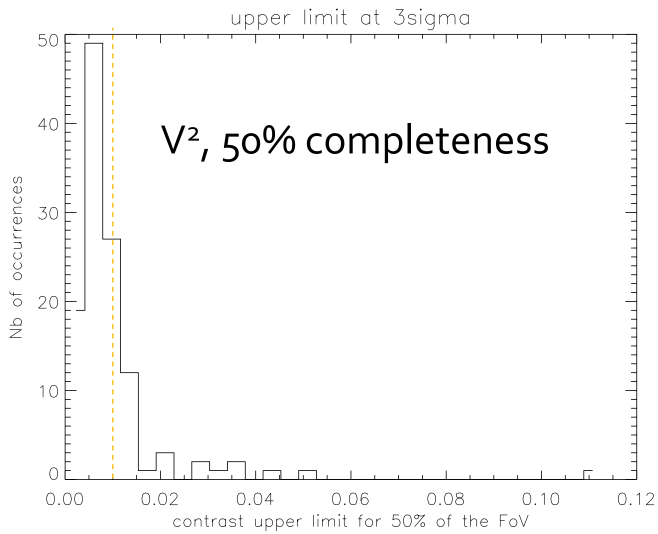


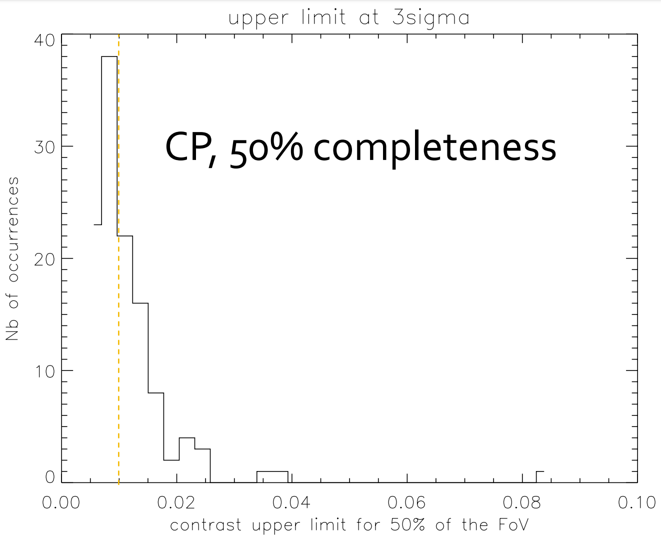
Marion et al., in prep

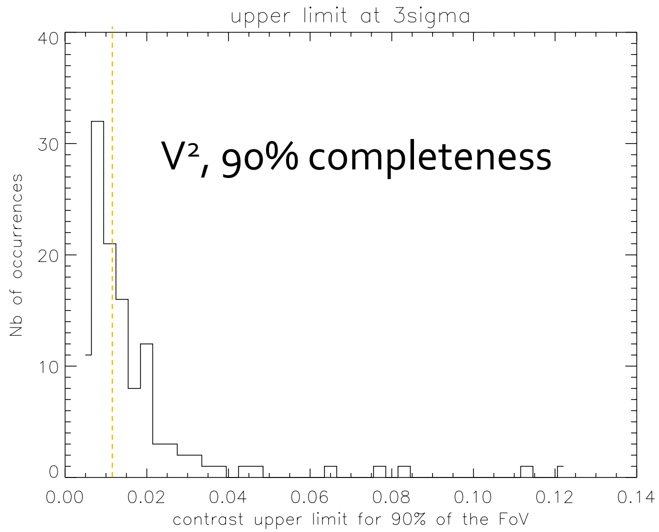
Binaries in the EXOZODI survey

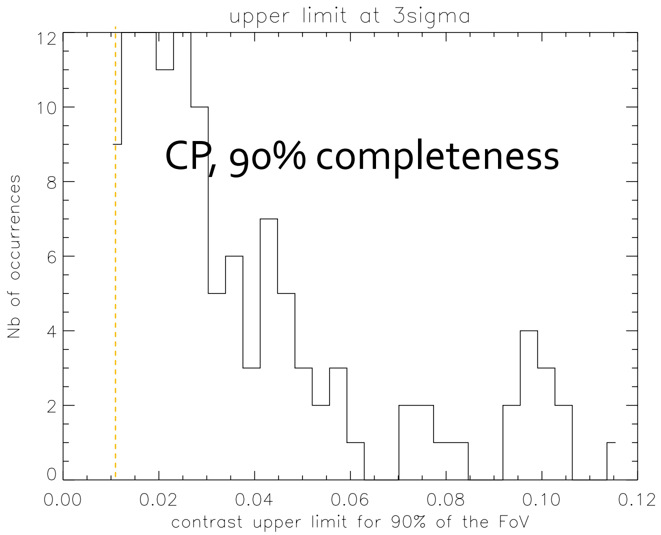
	Name	Date	Significance (cp+v2)	Significance (cp)	Significance (v2)	
A0IV	HD4150	17-12-2012	7.08	3.73	6.84	2%, 90 mas
		09-08-2013	22.52	29.25	43.84	
	HD7788	23-07-2012	7.29	1.88	13.51	
	HD15798	16-10-2012	5.96	1.98	13.83	
		09-08-2013	13.72	4.96	19.74	
A6V	HD16555	18-12-2012	106.20	28.04	219.17	50%, 80 mas
	HD20794	15-10& 12-12-2012*	4.47	1.51	6.59	
		10-08-2013	6.49	3.65	8.68	
		11-08-2013	3.58	3.53	5.48	
	HD23249	15-10& 16-12-2012*	11.59	3.36	20.51	
	HD28355	15-12-2012	4.31	2.44	5.58	
A6V	HD29388	16-12-2012	106.03	50.89	105.03	3%, 11 mas
	HD39060	16-10-2012	3.46	2.34	5.00	
		09-08-2013	3.87	2.23	4.35	
		11-08-2013	5.92	3.67	8.52	
	HD158643	08-08-2013	7.58	5.60	26.00	
		09-08-2013	9.14	2.74	13.69	
	HD173667	09-08-2013	3.98	1.47	5.69	
		11-08-2013	3.30	2.92	4.87	
	HD197481	08-08-2013	4.39	2.03	5.01	
A5V	HD202730	24-07-2012	11.47	8.58	21.02	95%, 65 mas
	HD216956	09-08-2013	5.04	2.23	6.04	
A1V	HD224392	26-07-2012	12.53	19.46	5.75	2%, ?? mas
		08-08-2013	20.06	3.58	22.93	
		09-08-2013	5.96	2.31	7.16	
		11-08-2013	10.50	6.25	11.53	

3σ sensitivity: V^2 vs CP

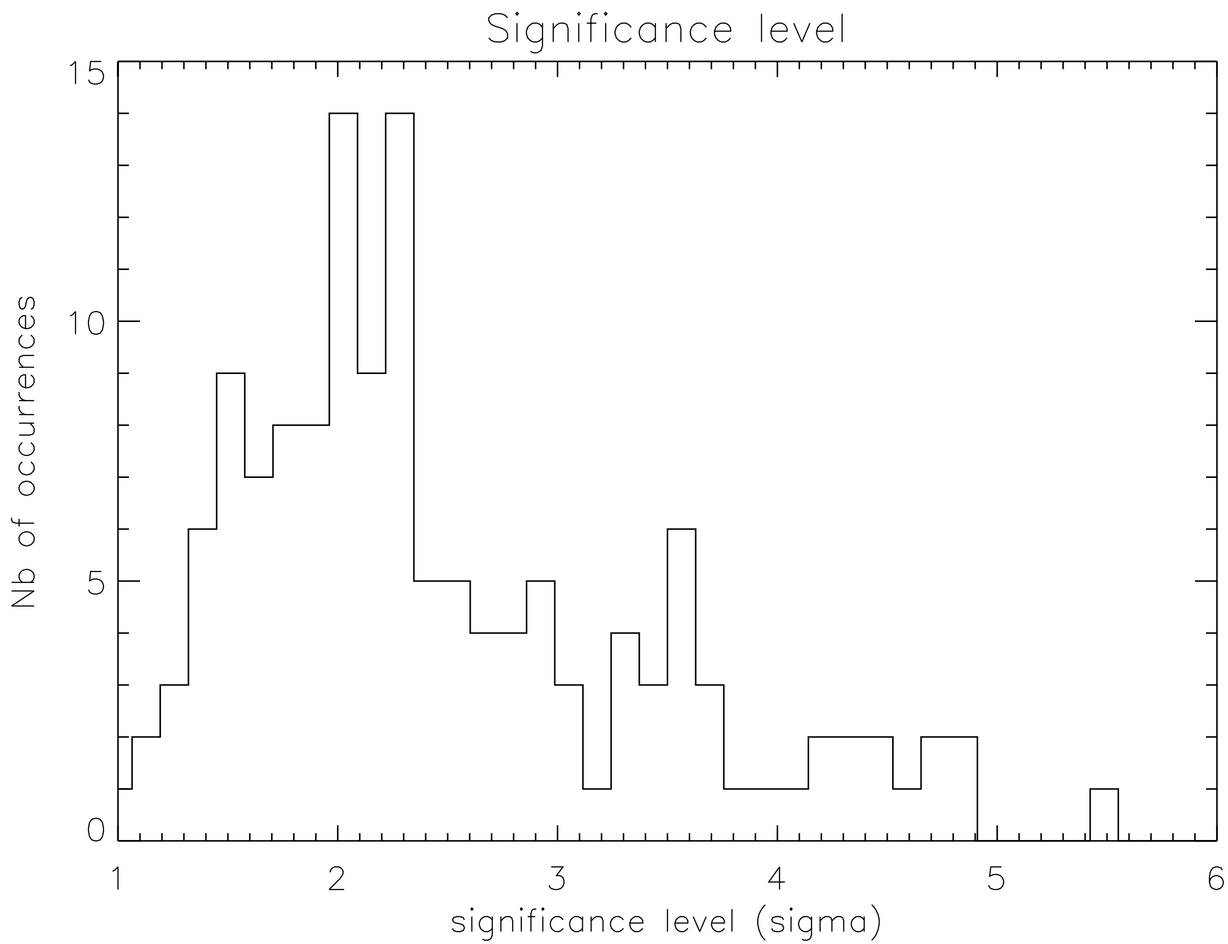




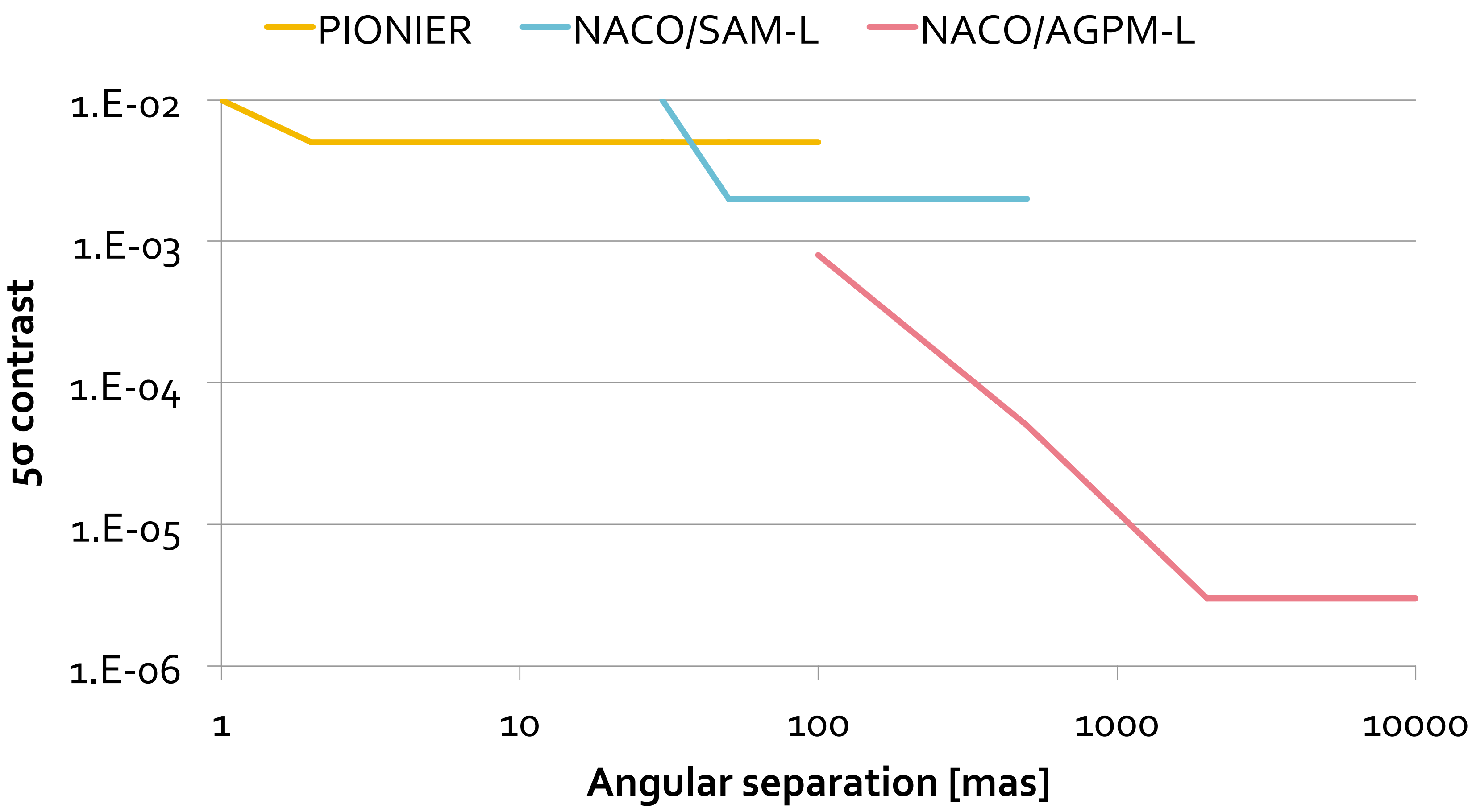




CP: 3σ, 4σ, or something else?



Summary



PIONIER
NACO/SAM-L
NACO/AGPM-L
1.E-02
1.E-03
1.E-04
1.E-05
1.E-06
5σ contrast
1
10
100
1000
10000
Angular separation [mas]