FLUOR science results and prospects

Vincent Coudé du Foresto

based on work from:

Rachel Akeson, Jason Aufdenberg, Hans Bruntt, David Ciardi, Denis Defrère, Emmanuel di Folco, Pierre Kervella, Anwesh Mazumdar, Antoine Mérand, Raphael Millan-Gabet, Stephen Ridgway…

l'Observatoire de Paris | LESIA

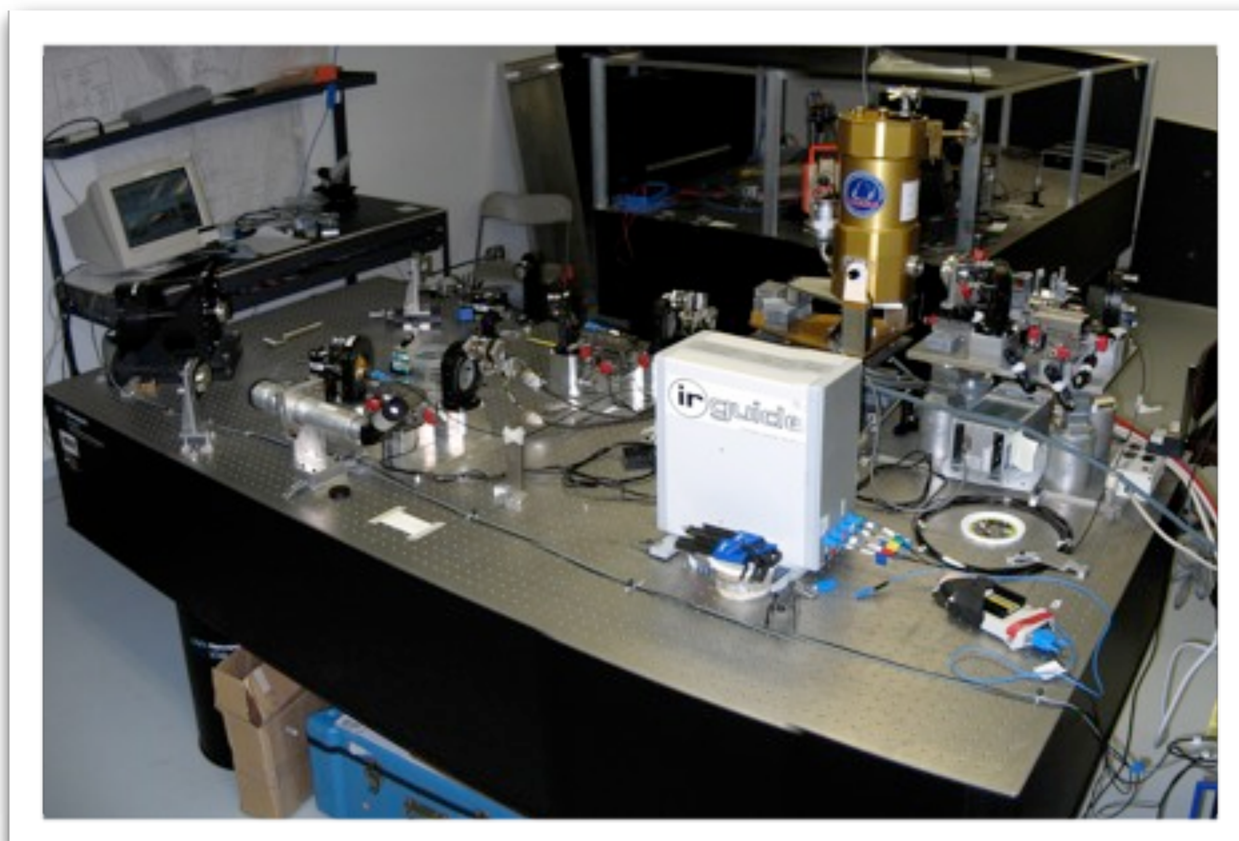
Laboratoire d'Études Spatiales et d'Instrumentation en Astrophysique

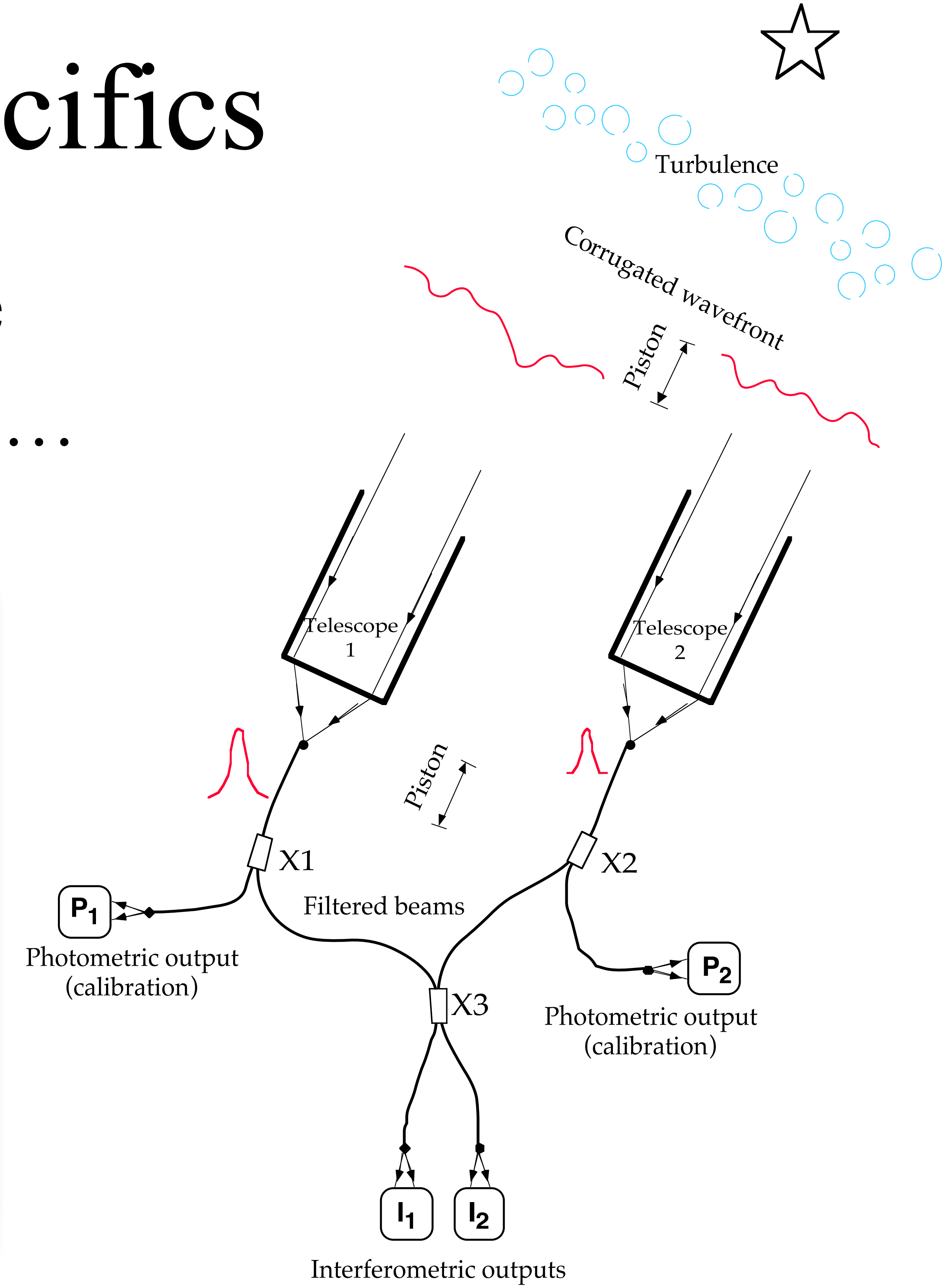
Outline

- FLUOR and 2009 observing overview
- Progress on debris disks
- Progress on Cepheids
- Other FLUOR related science
- Bibliography
- Advertisement

FLUOR specifics

- High accuracy V^2 science
  - Two telescopes so no phase…
  - Broad K band (so far)





Where does high accuracy V^2 matter ?

- For high dynamic range observations
  - Stellar environments (dust disks, molecular envelopes)
- To constrain simple models with high accuracy
  - Cepheid pulsations, fundamental parameters
- To discriminate between complex models
  - Cepheid atmosphere dynamics
- To reach beyond the λ/B limit
  - Small star diameters

Observations summary for 2009

- Proposals:
  - 2009-1 :
    - F1 (Debris disks): 13 nights (19-31 May)
    - F2 (Cepheids): 16 nights (25 June - 10 July)
    - F3/C12 (Ridgway, post-AGB disks): 5 nights (7-11 June)
    - F4/V15 (Ridgway, granulation of supergiants): 2 nights (11-12 June)
  - 2009-2
    - F1 (Debris disks): 9 nights (22-30 November)
    - F2 (Cepheids): 14 nights (1-14 October)
    - F3 (Be stars, rho Cas): 4 nights (26-29 October)

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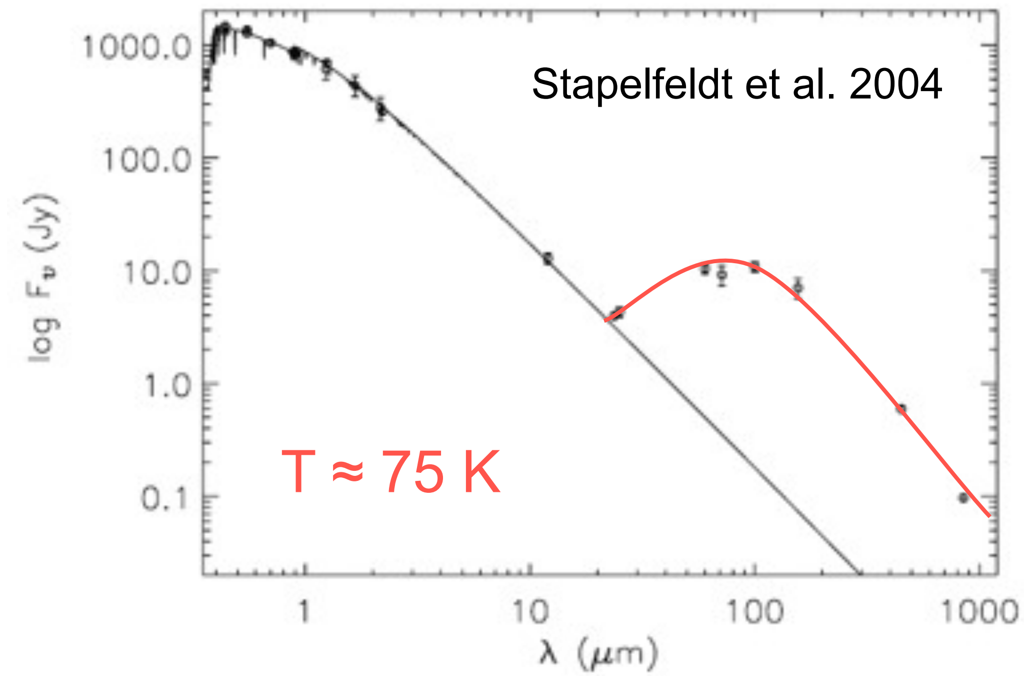
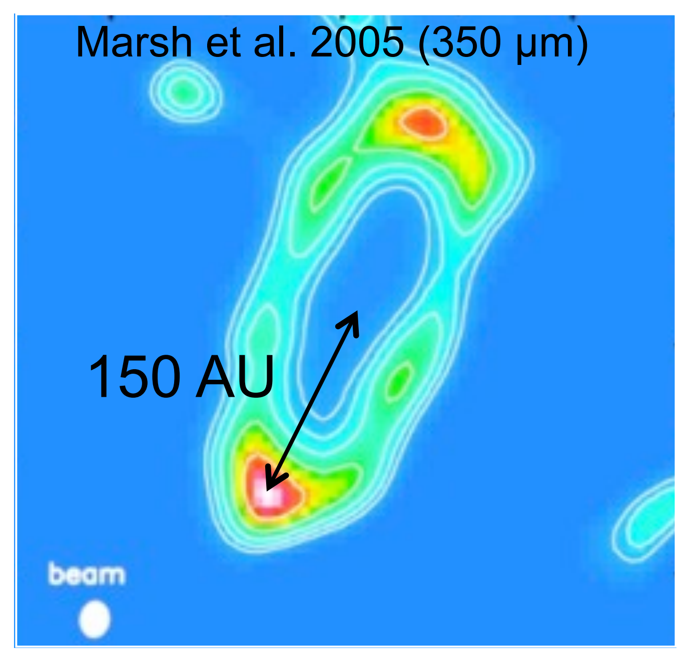
Debris disks

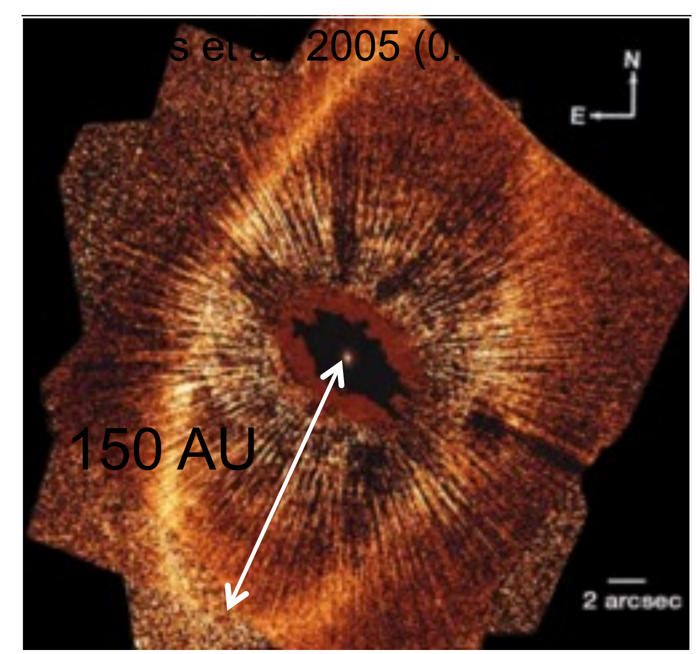
(150 AU ≈ 20’’ at 7.7 pc)

The quest for warm dust

- Detected debris discs
  - Far-IR, sub-mm, visible
  - Cold and distant (~100 AU)
  - Massive (few 100s × Kuiper belt)
  - Evidences for inner holes
- Zodiacal disc analogues?
  - Inner planetary region
  - Spitzer: first evidence for warm dust (~300 K)
  - Sensitivity ~ 1000 zodi!
- Need direct imaging of exozodiacal discs in the planetary region
  - Towards future exoearth imaging space missions…



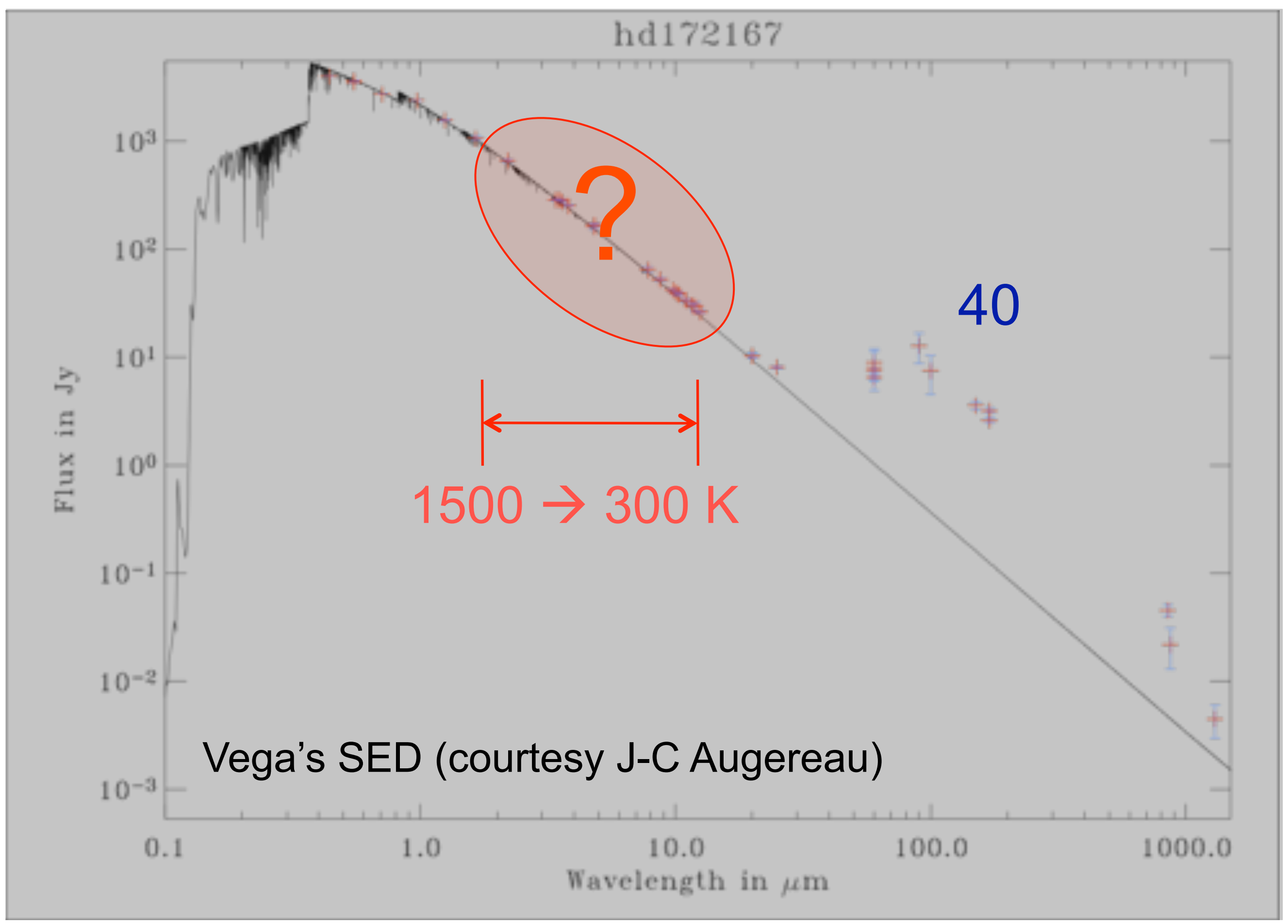


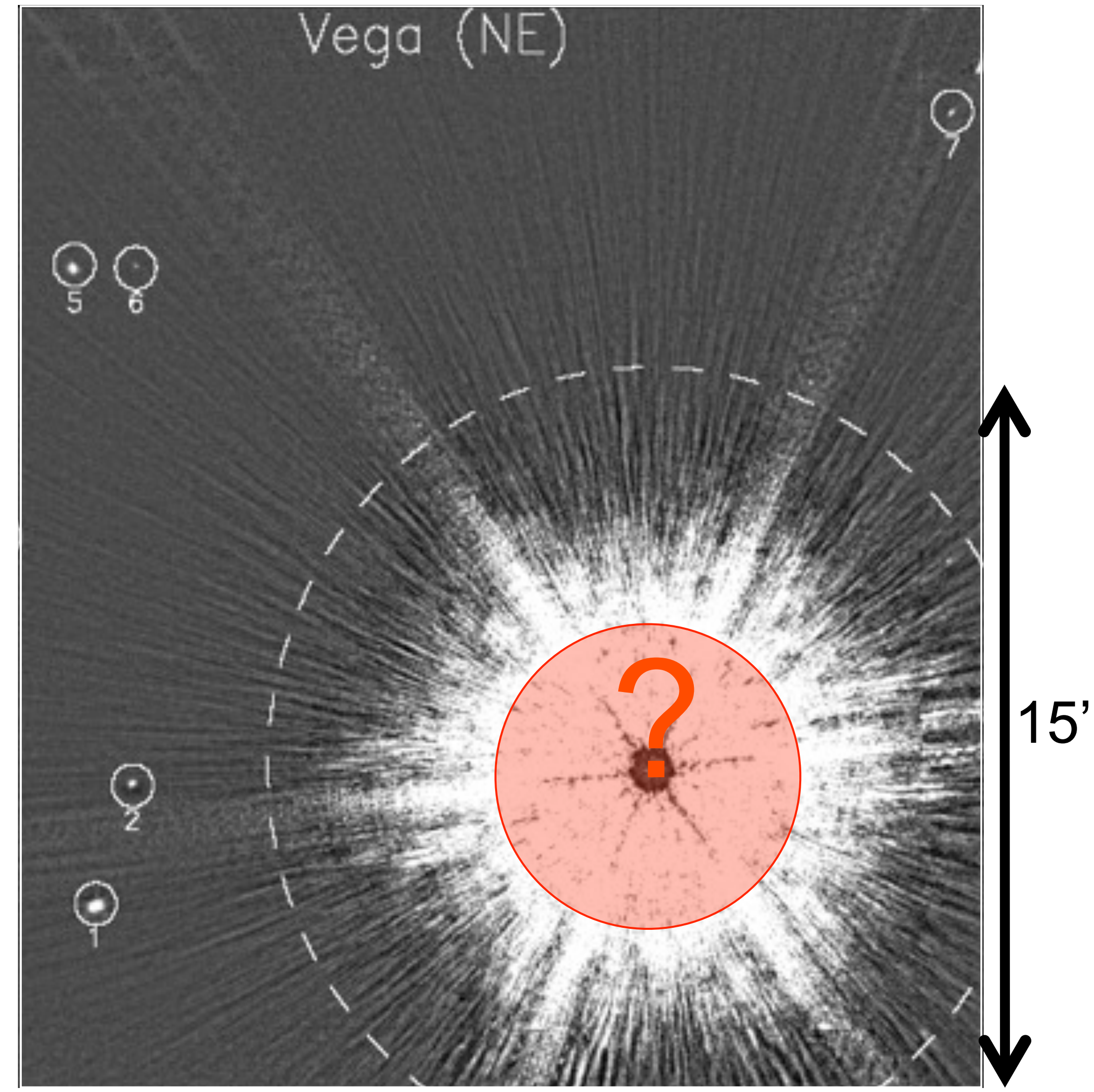


(150 AU ≈ 20” at 7.7 pc)

Detecting hot dust in inner debris disks

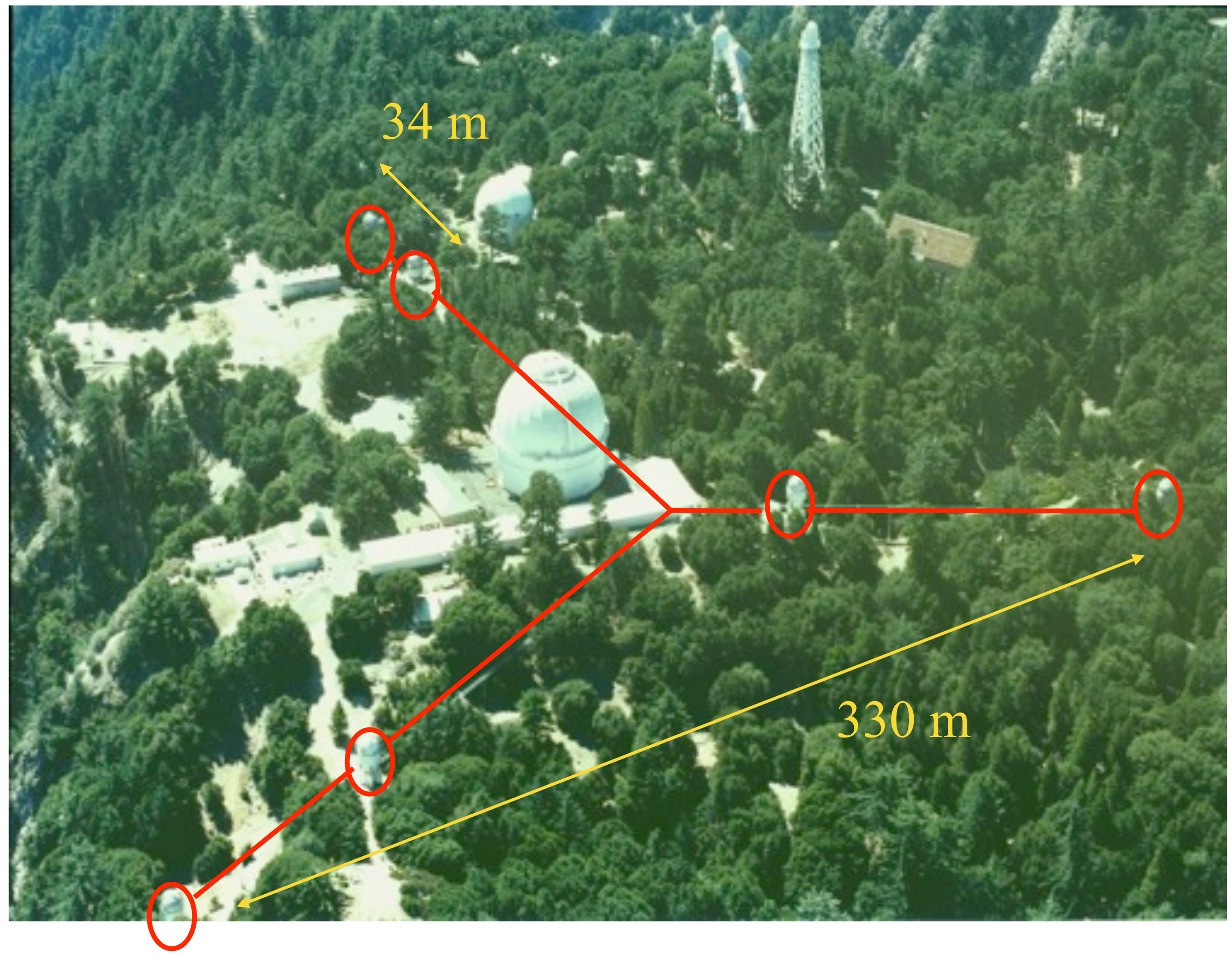
- High contrast (≥ 1:100)
- Small angular separation
  - Inner disc: a few 10 mas
  - Requires IR interferometry





Macintosh et al. 2003 (Keck AO)

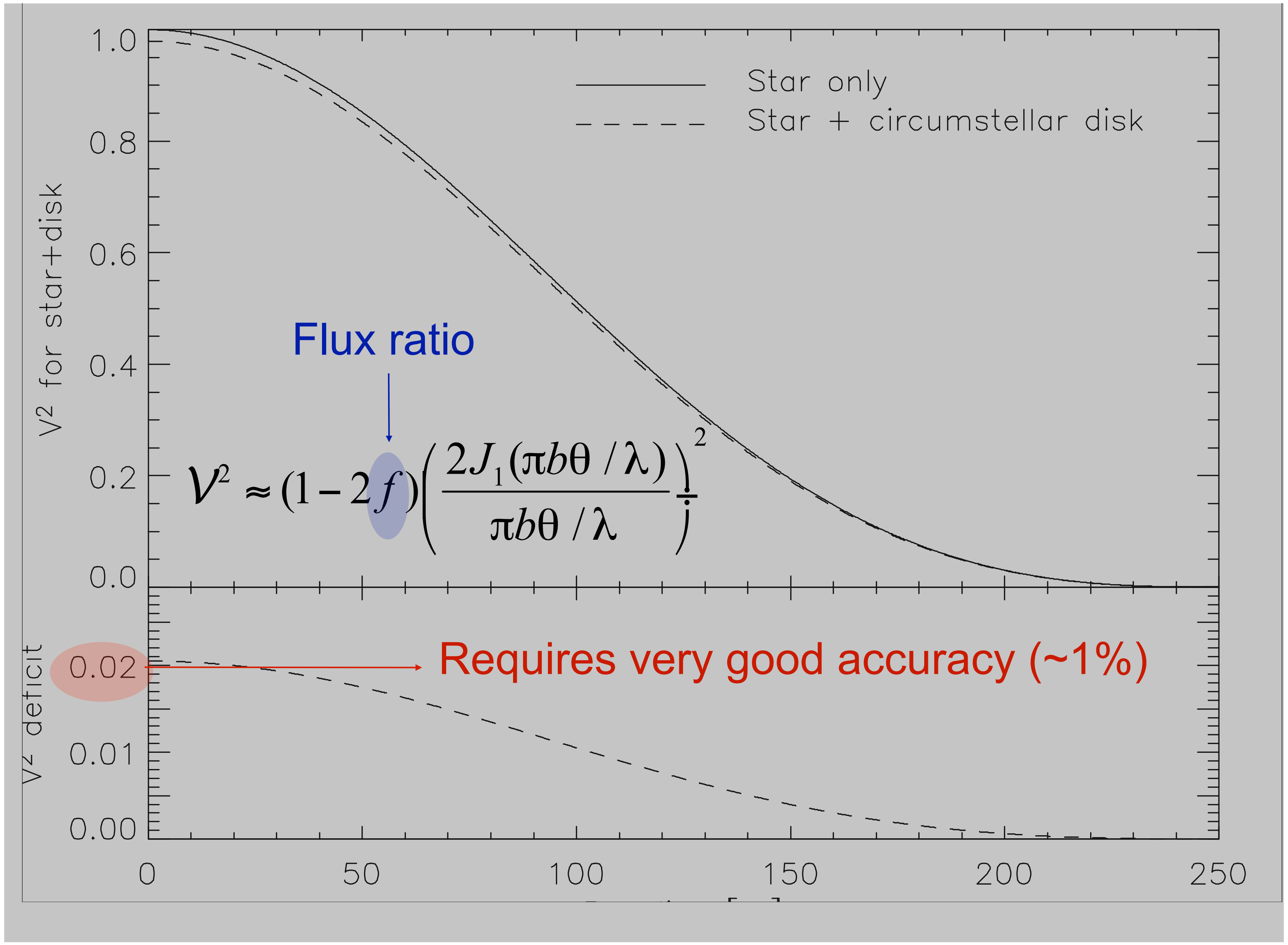
Survey of debris discs with CHARA/FLUOR



Survey of ~40 bright MS stars (K < 4) with known, cold debris discs or not

13 G-K stars | 12 F stars | 14 A stars

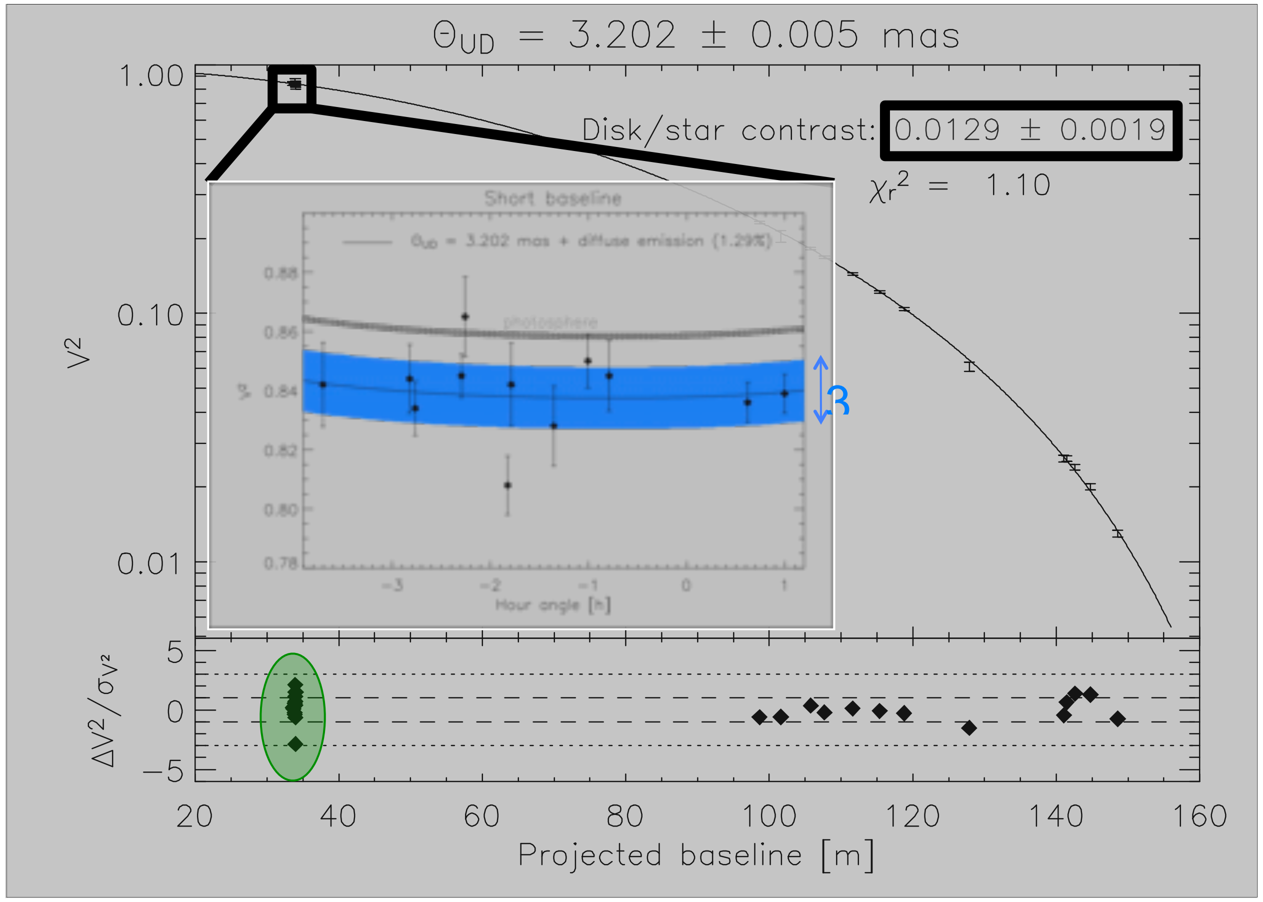
Interferometric signature of a disk

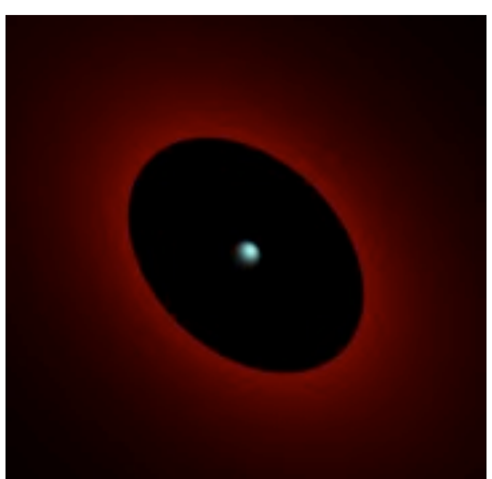


- Disc larger than angular resolution (λ/b) → incoherent flux
- Induces a visibility deficit at all baselines
- Best detected at short baselines

Vega : the first robust detection

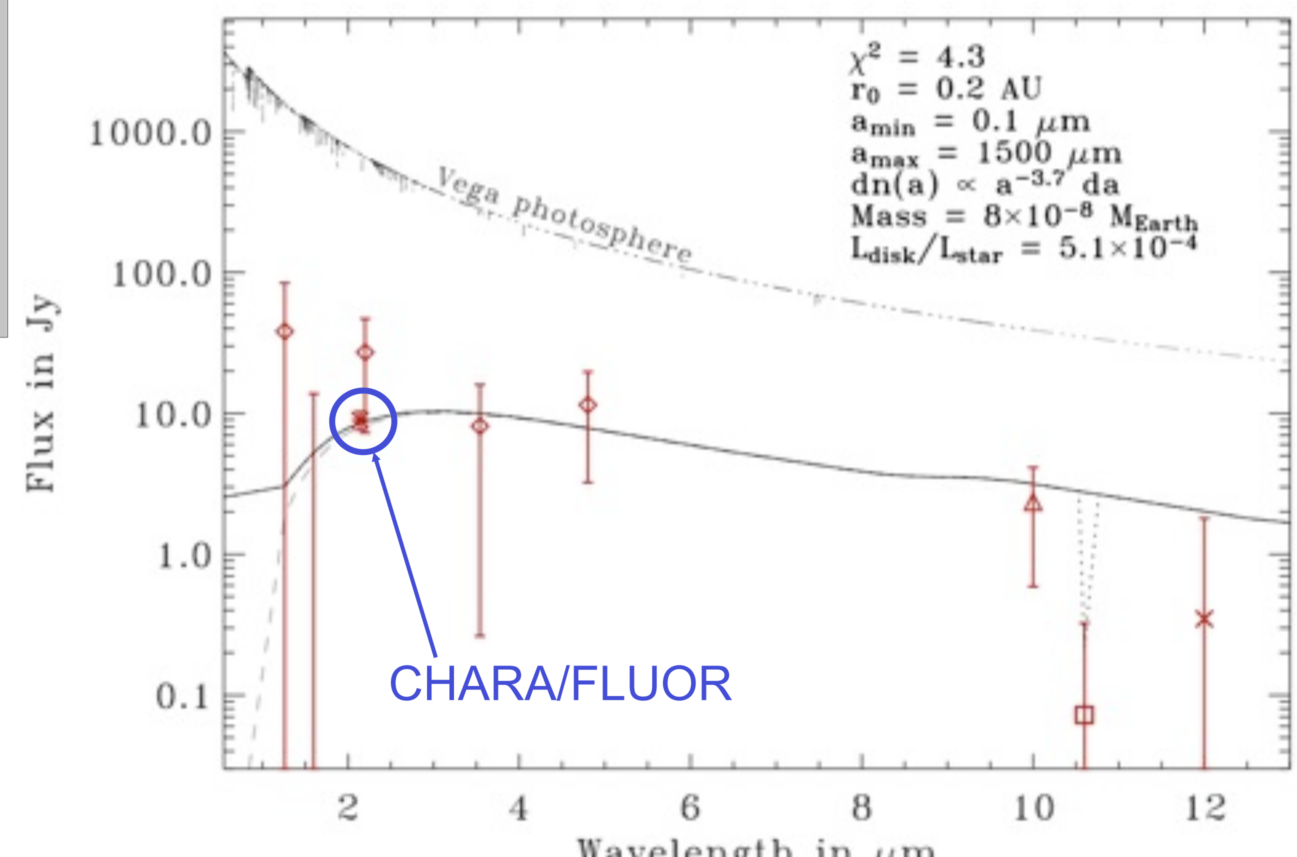
*Absil et al. 2006, A&A **452**, 237*





Model picture of Vega system as seen by CHARA / FLUOR

- 1.3% incohent flux detected
- Combined with spectroscopic data yields:
  - Grains are small (<1µm)
  - M_{dust} = 8 .10^{-8} M_{earth} in the inner 10AU
- Vega also flattened fast rotator, with equator 2250K cooler than the pole (Aufdenberg et al. ApJ 2006)

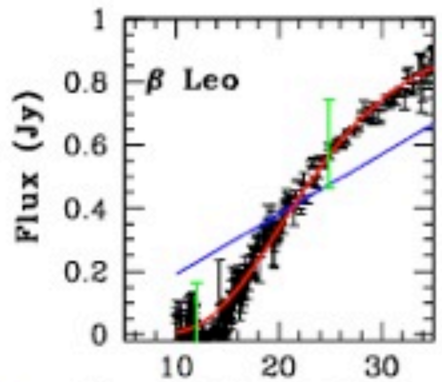


Other A stars - β Leonis and ξ Leporis

Akeson, Ciardi, Millan-Gabet et al. 2009, ApJ ***691****, 1896*

β Leo

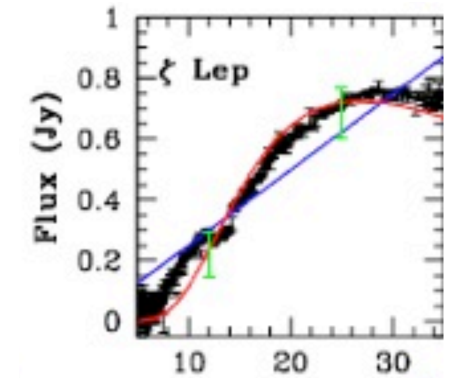
IRAS discovered
A3V ~80 Myr @11 pc
IRAS discovered
+IRS T~120K, R~19AU (Chen2006)



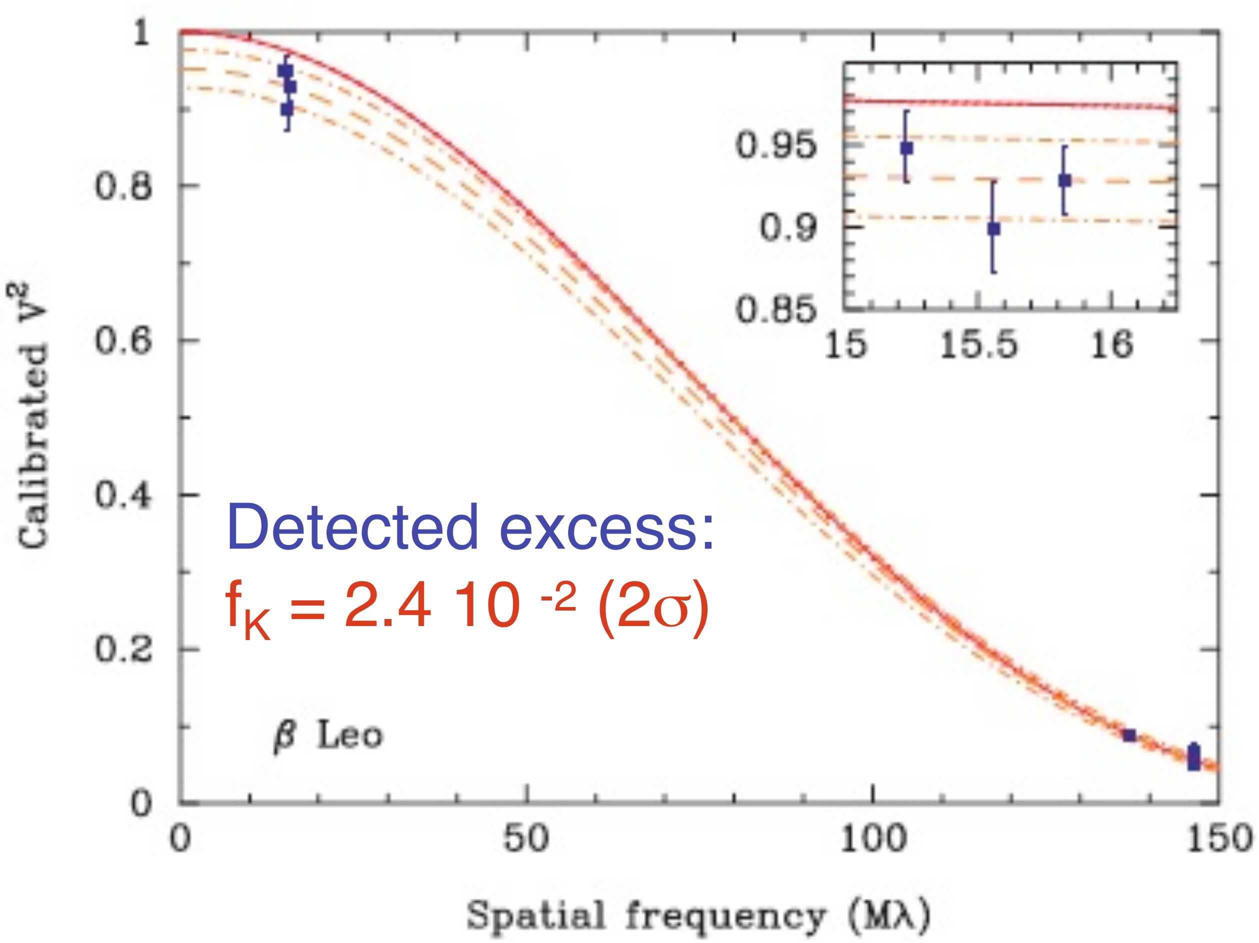
Chen et al (2006)

ζ Lep

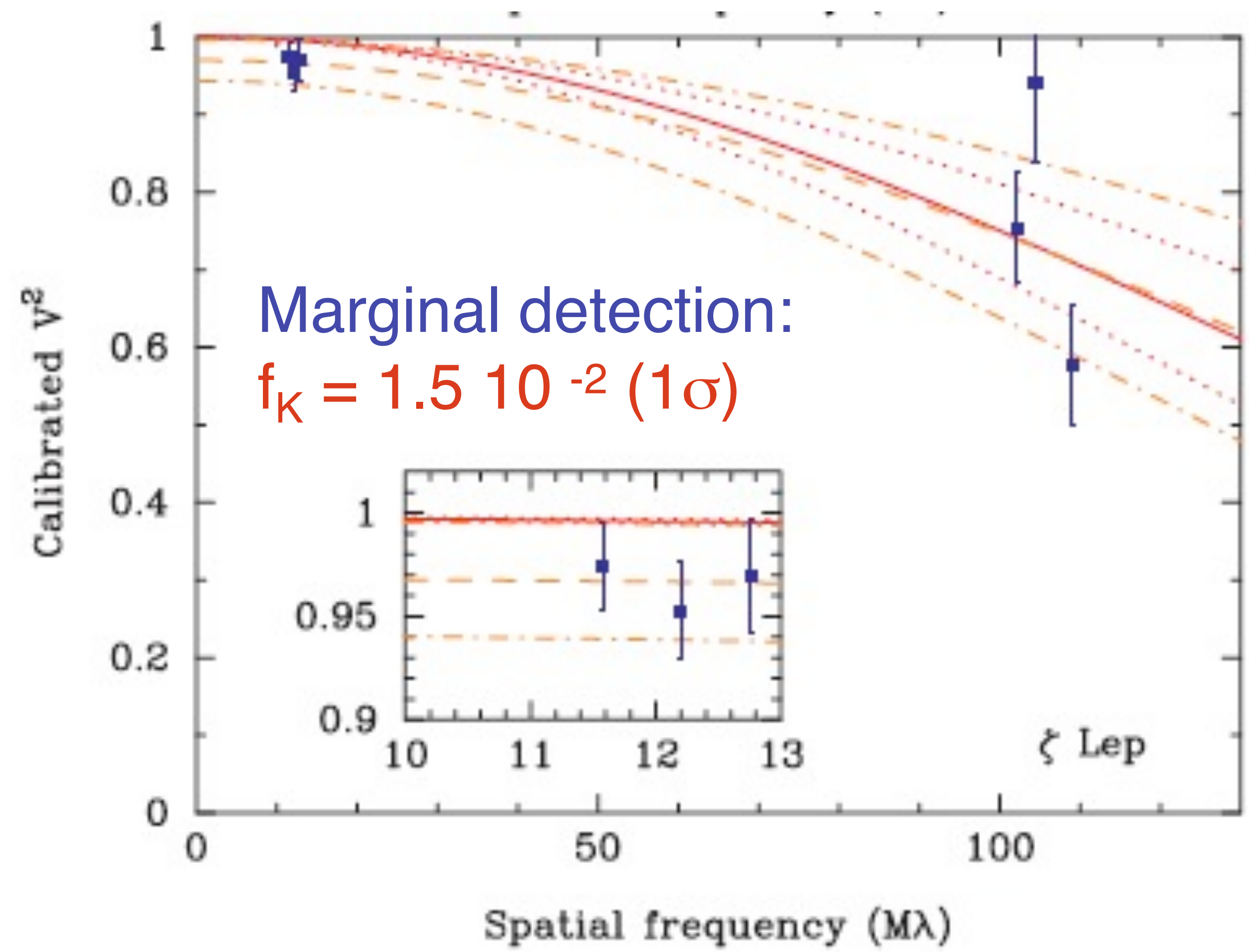
IRAS discovered
A2V 200Myr @20 pc
IRAS discovered
+IRS excess, warm dust
T~300K, R~2-8AU (Chen2006)
Resolved@18μm (Moerchen2007)



Chen et al (2006)



Detected excess:
f_K = 2.4 10 $^{-2}$ (2σ)



Marginal detection:
f_K = 1.5 10 $^{-2}$ (1σ)

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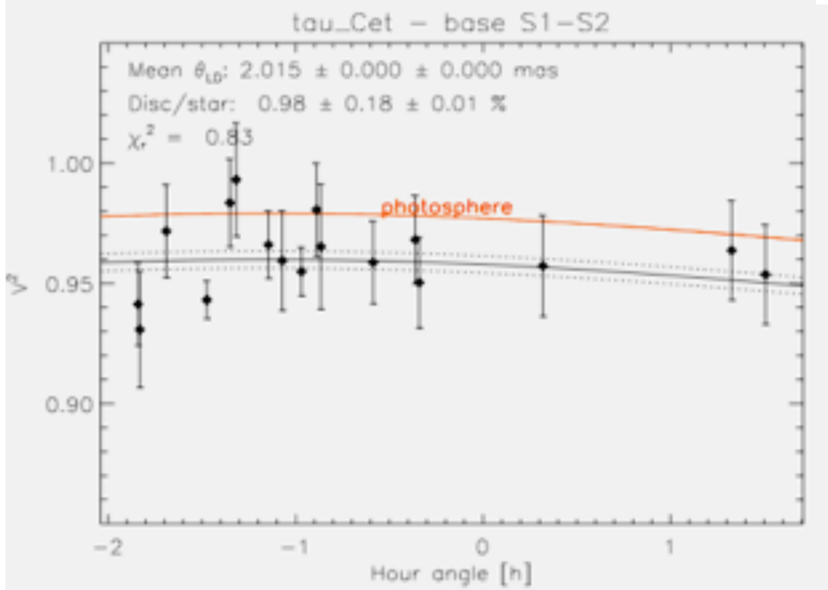
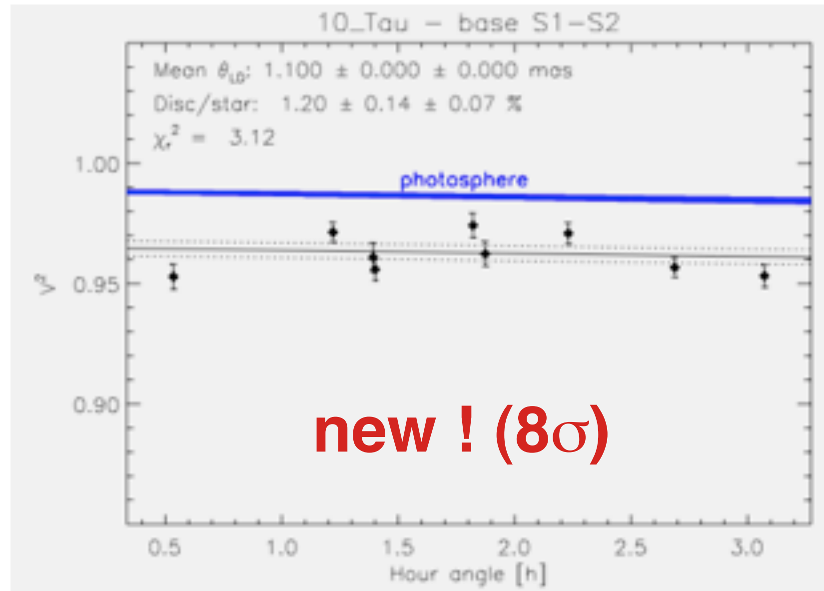
F-G-K detections

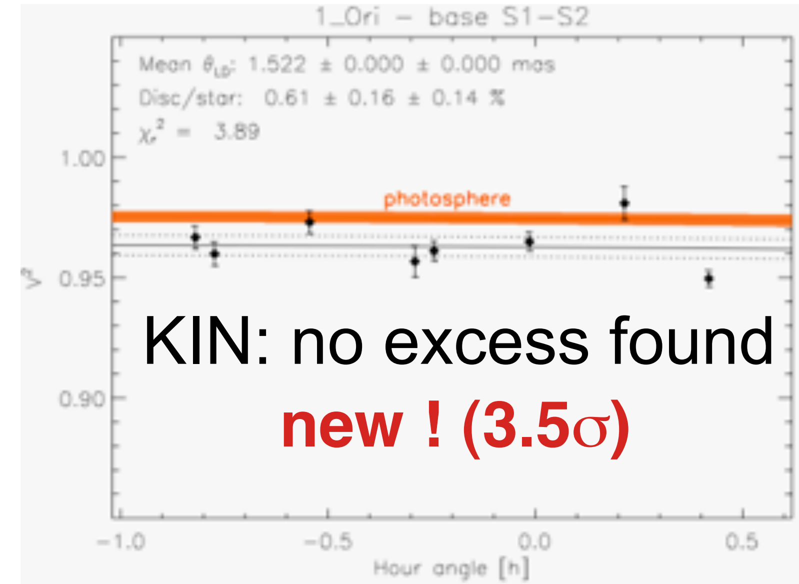
τ Cet, G8V, cold dust, no planet

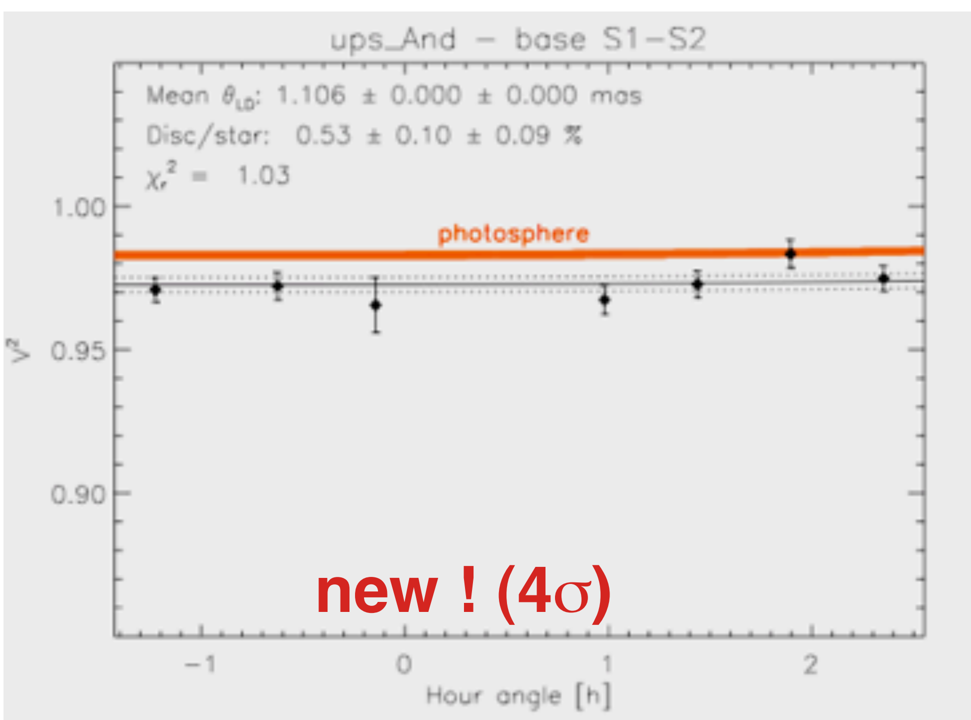


10 Tau, F9V, cold dust, no planet

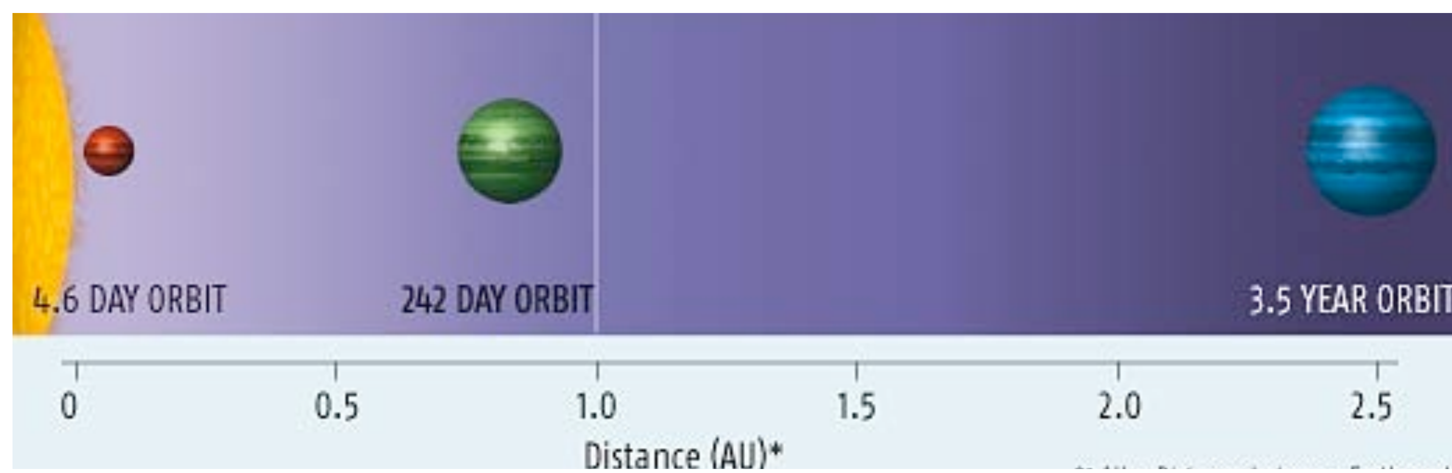


1 Ori, F6V, no dust, no planet



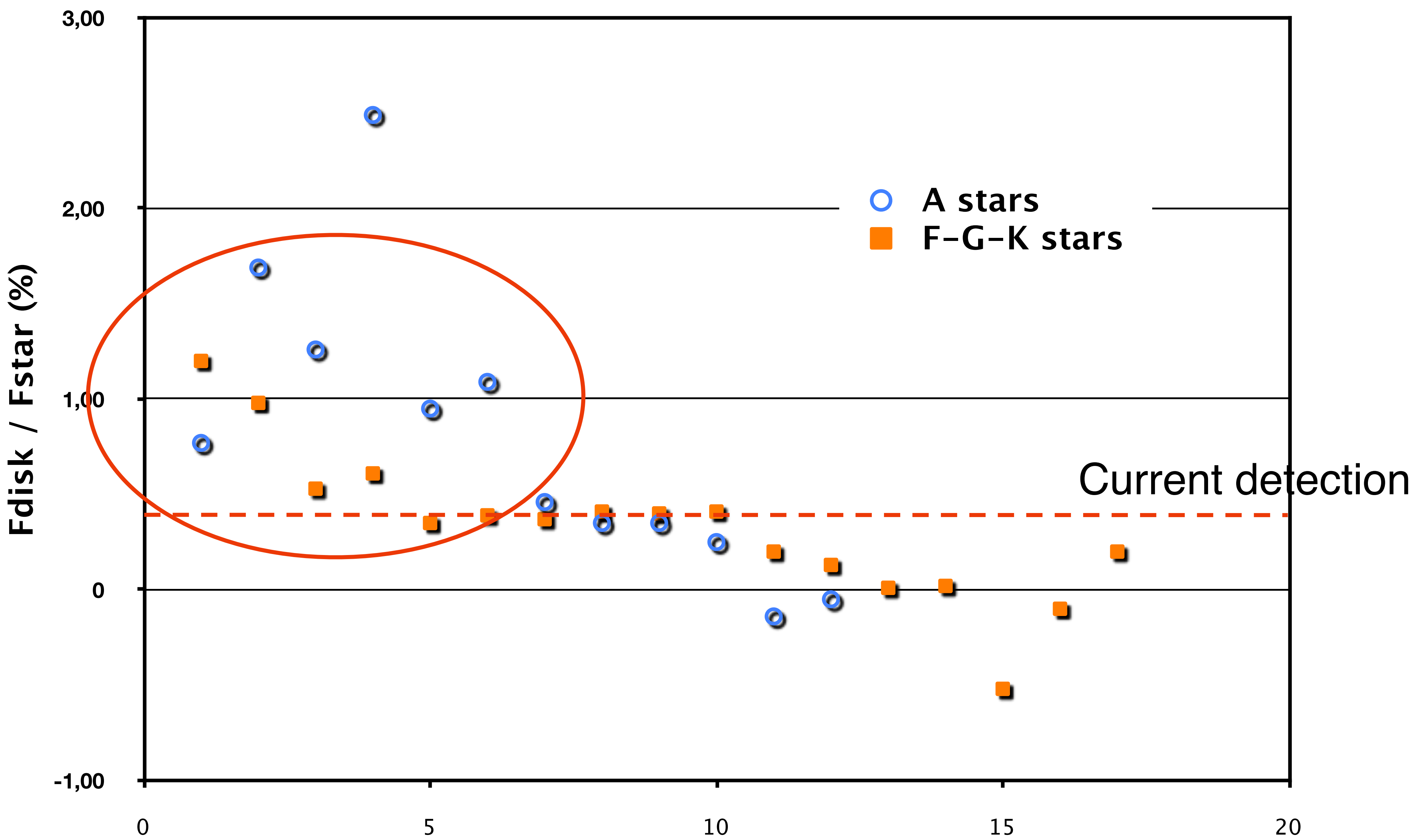


υ And A, F8V, 3Gyr: no cold dust but 3 known planets !



Is this really a ring of dust between the planets ?
(no mid-IR emission detected…??)

Detection Summary



Preliminary statistics

- Adding Fomalhaut's exozodi (VINCI data)
- Frequency vs. spectral type
  - A-type stars: 45%-64% (± 14%)
  - F-type stars: 20%-50% (± 15%)
  - G- and K-type stars: 11% (± 17%)
- Frequency vs. cold dust
  - Stars with cold dust: 29%-47% (± 11%)
    - 6/17 (including 1 strange case) + 2 marginal detections
  - Stars "without" cold dust: 21%-36% (± 13%)
    - 5/14 (including 1 possible cirrus + 1 possible binary)

Possible bias ?

- Check population at < 3σ (19 stars)
  - 10 positive excess, 9 negative excess
  - Mean excess: 0.01% ± 0.55%
  - Mean error on excess: 0.42%
  - Mean significance of excess: 0.15σ
- Statistical dispersion seems mostly sane
- Very small bias toward positive excesses
  - No underlying population of small excesses???

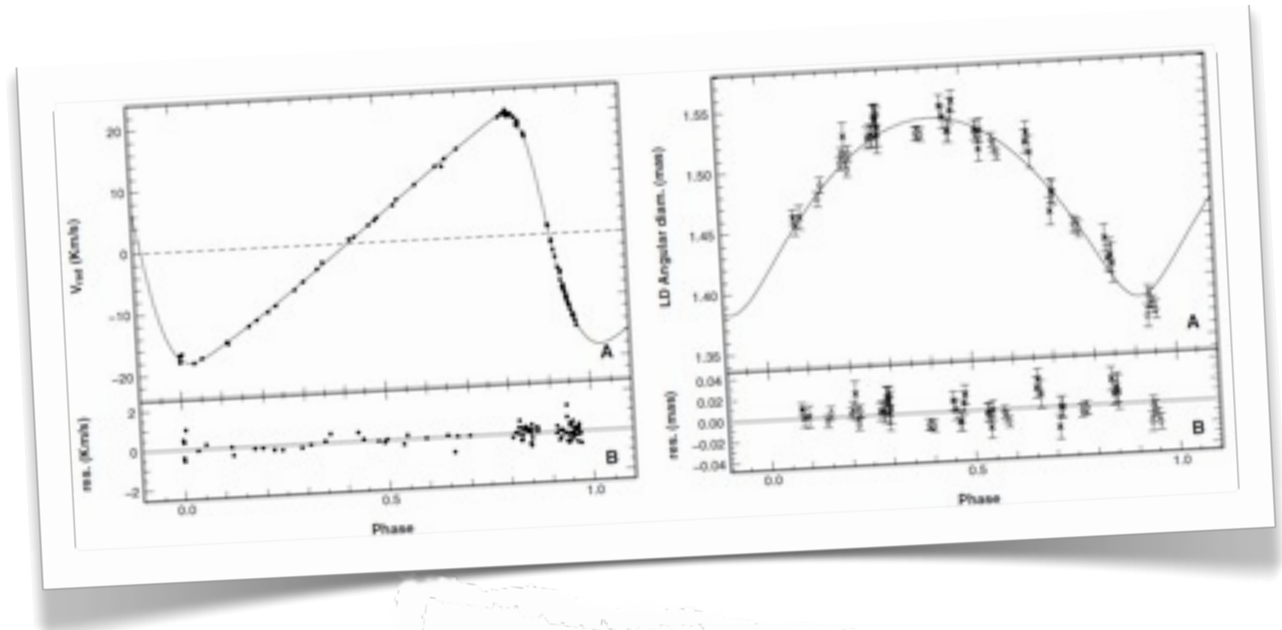
What’s next ?

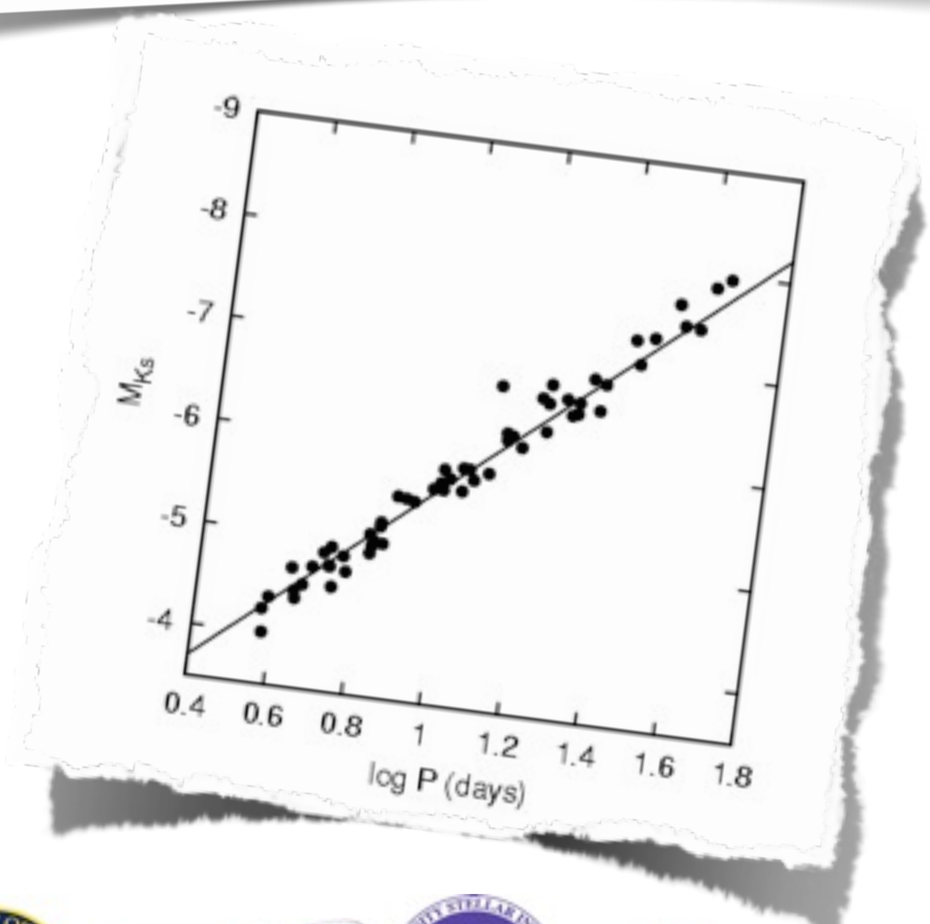
- List of debris disk stars (K<4, dec>-10°, no SB)
  - 18 A / late B stars (10 are TBD)
  - 7 F stars (2 are TBD)
  - 10 G / K stars (4 are TBD)
- Handle TBDs of 16/35 debris disks stars
  - Checking asymetries with MIRC
- Need to increase control sample similarly
- At least 2 more years of FLUOR!
- … and then:
  - return on proven detections (time changes ?)
  - deeper search (based on dynamic range improvements)

Cepheids

Cepheids

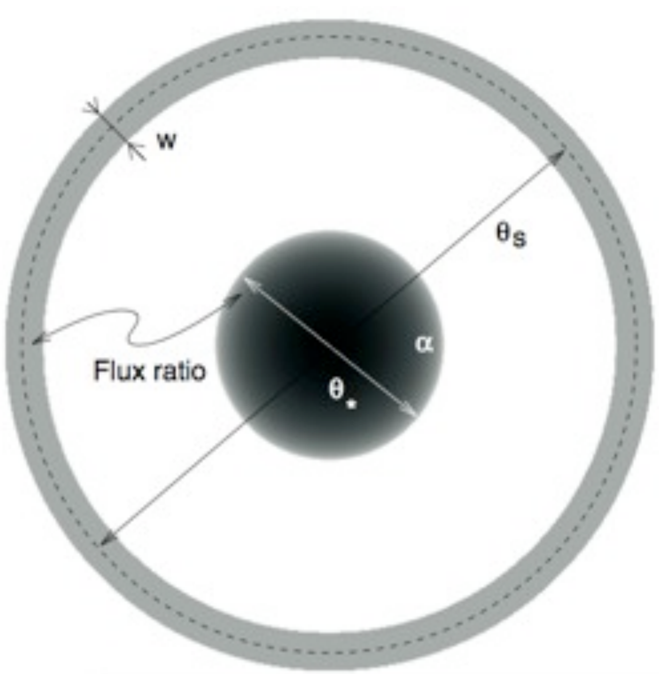
- Interferometry has the potential to provide distances of a few 10s of nearby Cepheids to 1-4%
- Objective: calibration of the period-luminosity relation to 1% by the end of next year
- But... Cepheids are more complex objects than expected...



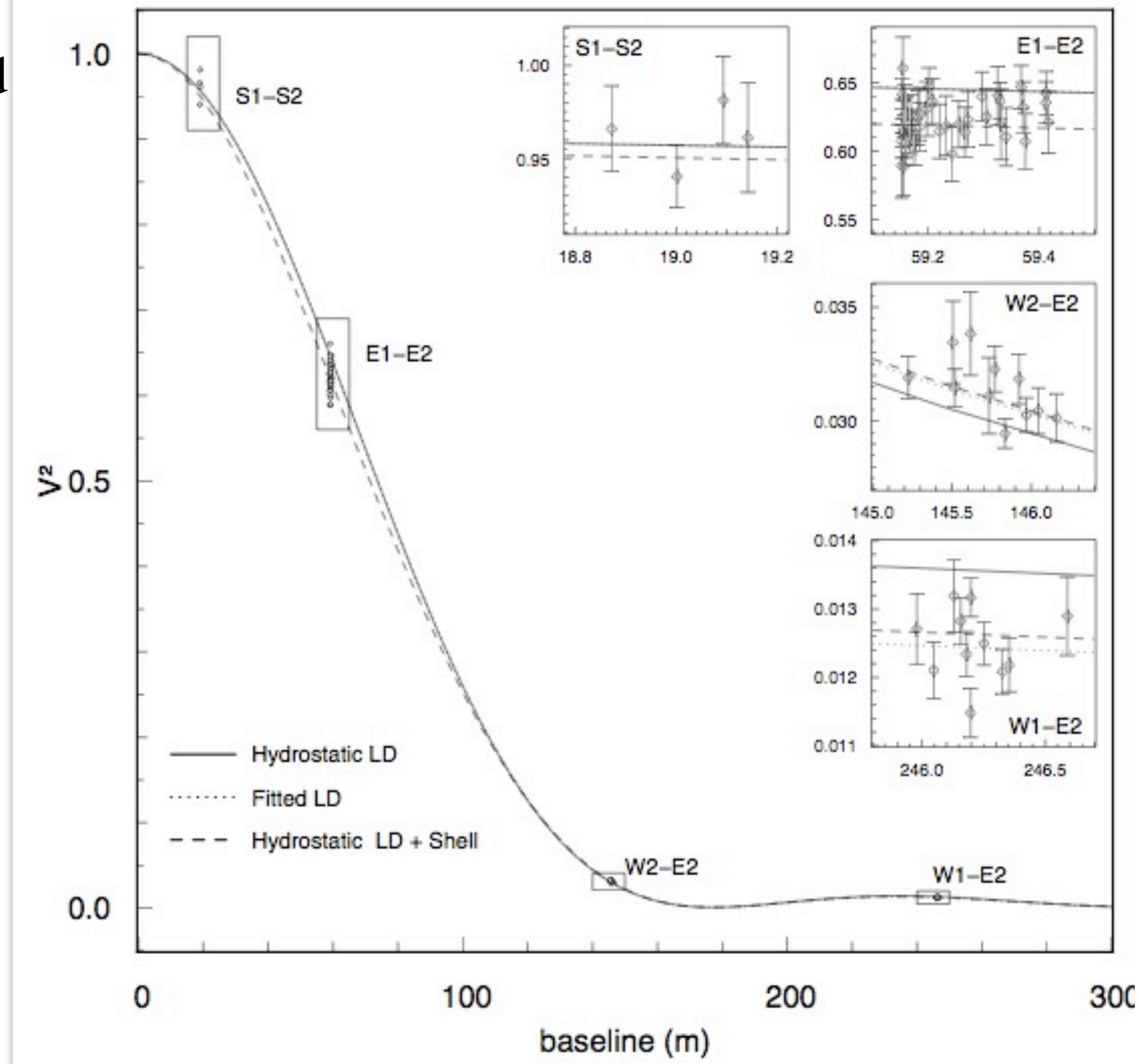


Example : Polaris

- Polaris:
  - very low amplitude Cepheid
  - first overtone
- CHARA/FLUOR:
  - limb darkening much stronger than models
  - deficit around V^2=65%
- LD alone cannot explain the mid-range baselines visibility deficit



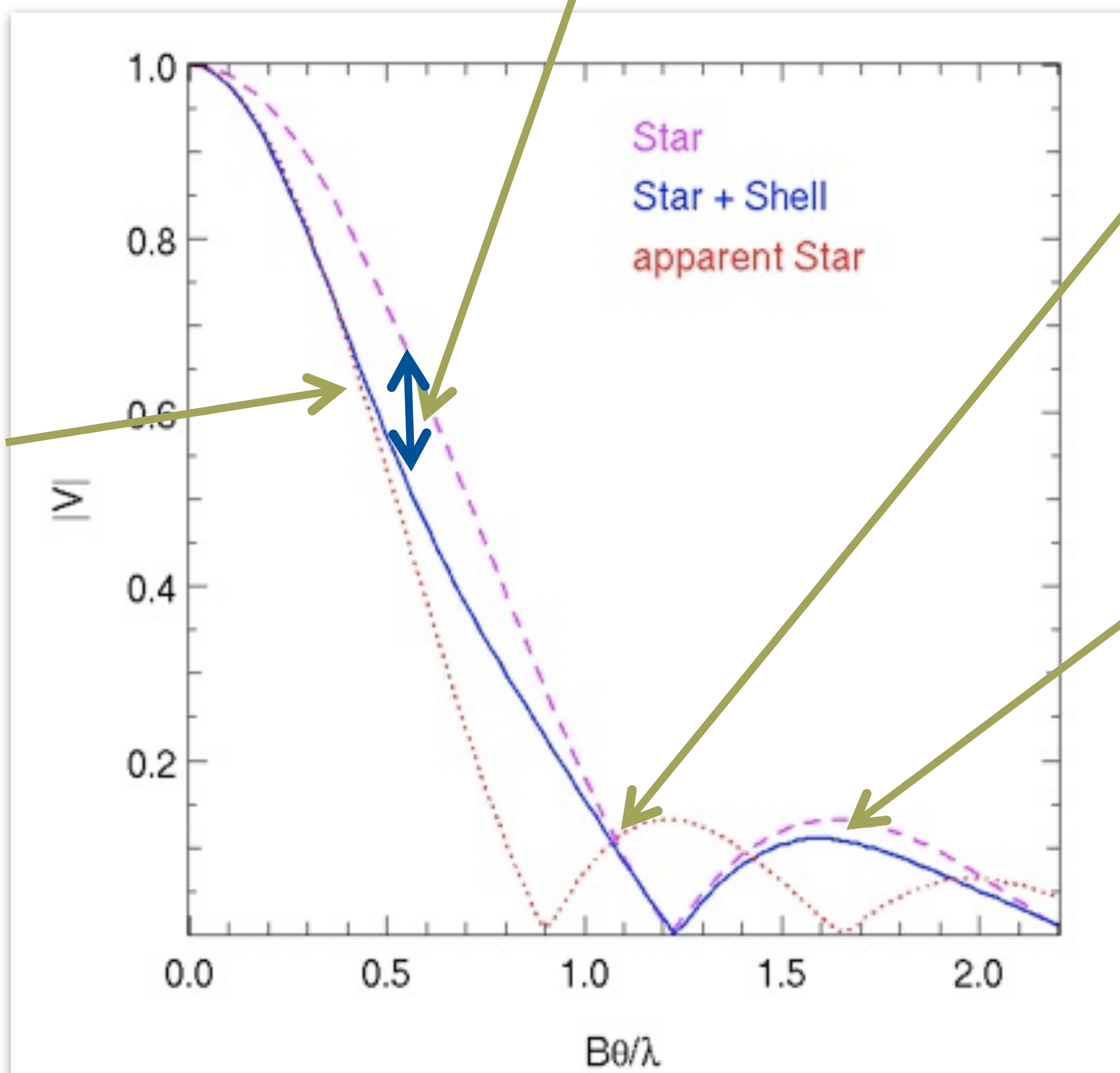
Mérand et al. 2006, A&A ***453****, 155*



Effects of the envelope on the fringe visibility

Position ~ R_{shell} / R_{star}
Depth ~ F_{shell} / F_{star}

1) The star appears larger on short baselines

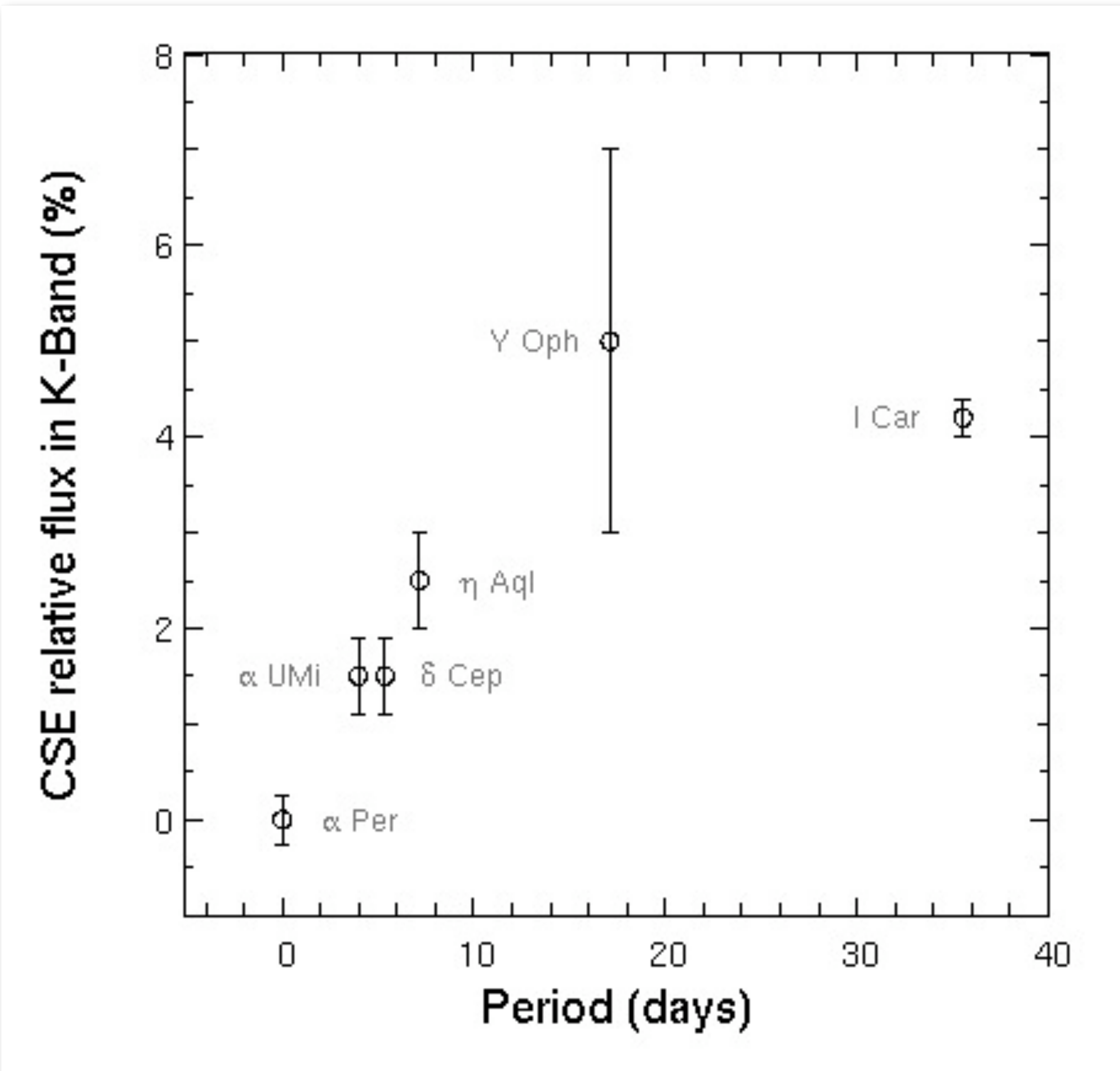


Effect 1) disappears for low visibility

2) The limb darkening appears stronger

An interesting correlation

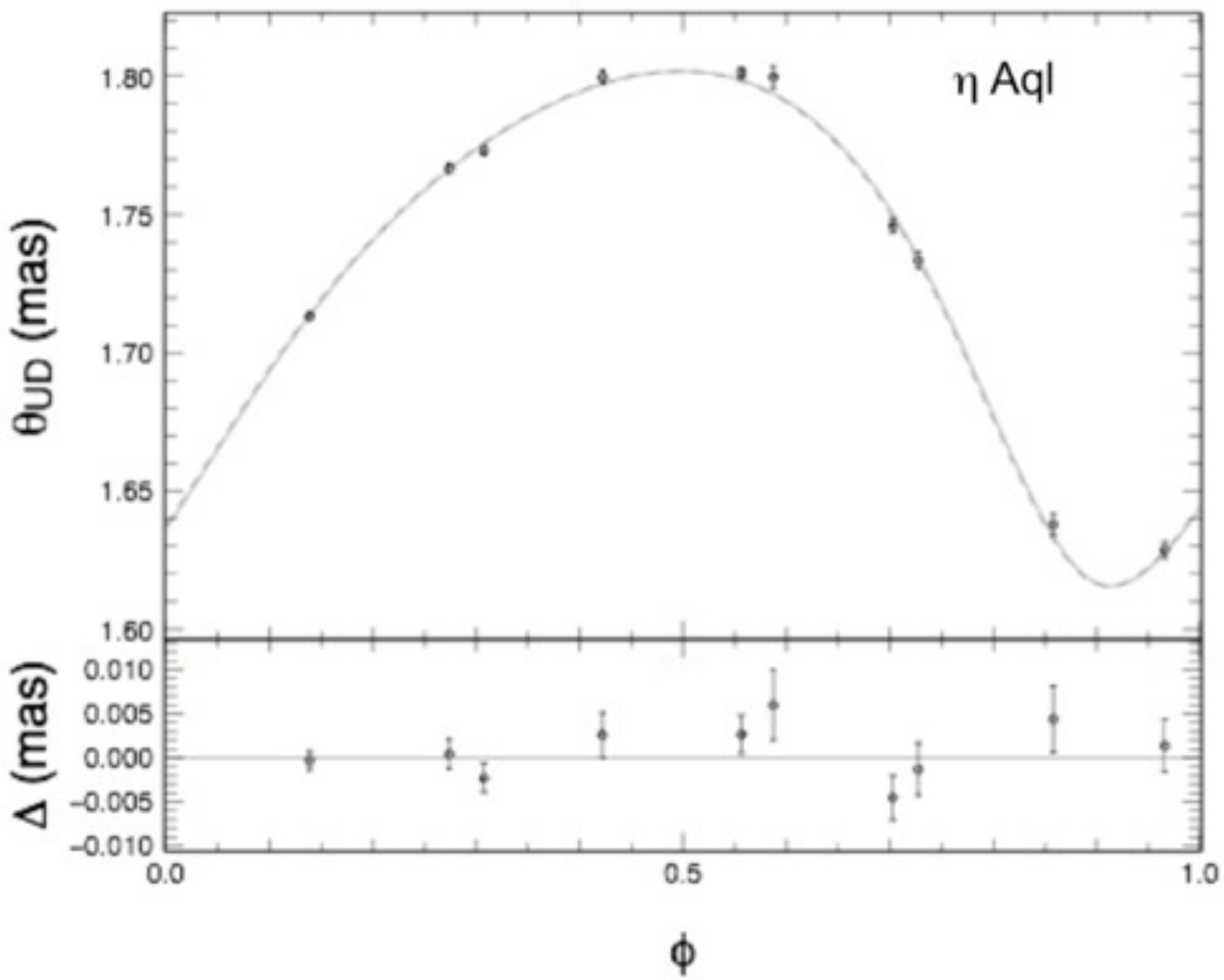
Kervella et al.



- Correlation beween $F_{env.}/F^*$ and period
- M, L, R ↗
- T_{eff}, g ↘
- Mass-loss linked to pulsation ?
- Typical envelope size ~ 3 R*

Next: testing a comprehensive model of the Cepheid phenomenon

eta Aql by CHARA / FLUOR



- Photosphere
- Envelope
- Dynamical effects in the atmosphere
  - Compression of line-forming regions around the minimum angular diameter

Other FLUOR science

A&A 503, 521–531 (2009)
DOI: 10.1051/0004-6361/200912351

Astronomy & Astrophysics

Asteroseismology and interferometry of the red giant star ϵ Ophiuchi

A. Mazumdar[1,2,3], A. Mérand[4,5], P. Demarque[2], P. Kervella[6], C. Barban[6,1], F. Baudin[7], V. Coudé du Foresto[6], C. Farrington[5], P. J. Goldfinger[5], M.-J. Goupil[6], E. Josselin[8], R. Kuschnig[9], H. A. McAlister[5], J. Matthews[10], S. T. Ridgway[11], J. Sturmann[5], L. Sturmann[5], T. A. ten Brummelaar[5], and N. Turner[5]

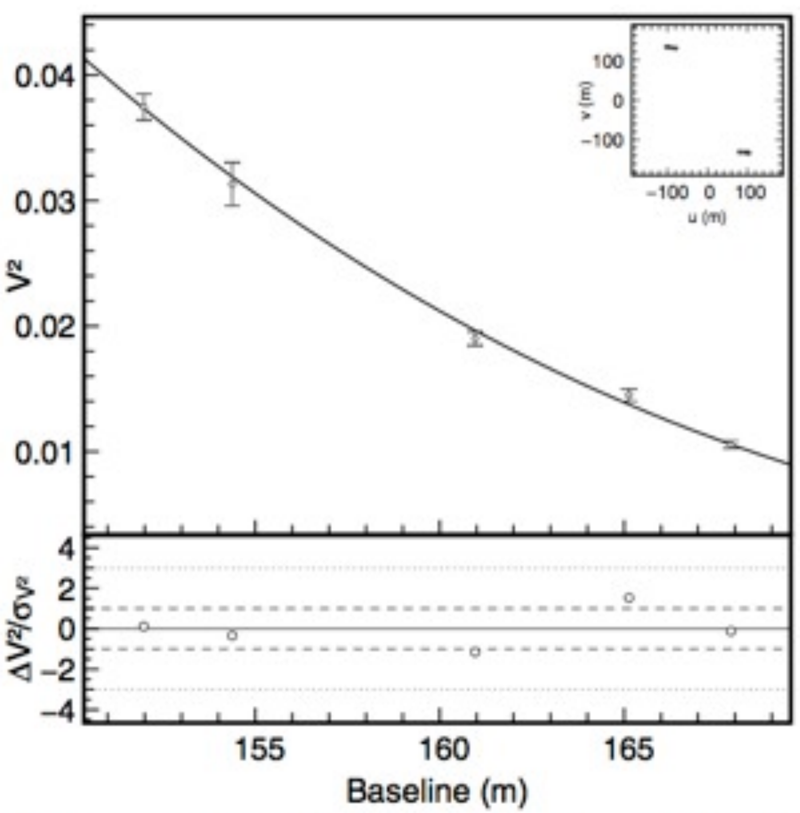


Fig. 7. Squared visibilities and adjusted limb darkened disk visibility model for ϵ Oph (see also Table 3). The lower panel shows the residuals to the model, with 1σ (*dashed line*) and 3σ (*dotted line*) limits. The *inset* panel shows the (u, v) coverage. Note that the error bar given here is the formal error bar: we added some systematics for final result (see text).

- Diameter of ε *Oph* measured by CHARA/FLUOR (2.961 ± 0.007 mas)
- Hipparcos parallax converts this to photospheric radius $R = 10.39 \pm 0.07\ R_\odot$
- This confirms the (model dependent) radius obtained from the analysis of MOST asteroseismic data

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The radius and effective temperature of the binary Ap star β CrB from CHARA/FLUOR and VLT/NACO observations★

H. Bruntt[1,2], P. Kervella[1], A. Mérand[3], I. M. Brandão[4,5], T. R. Bedding[2], T. A. ten Brummelaar[6], V. Coudé du Foresto[1], M. S. Cunha[4], C. Farrington[6], P. J. Goldfinger[6], L. L. Kiss[2,7], H. A. McAlister[6], S. T. Ridgway[8], J. Sturmann[6], L. Sturmann[6], N. Turner[6], and P. G. Tuthill[2]

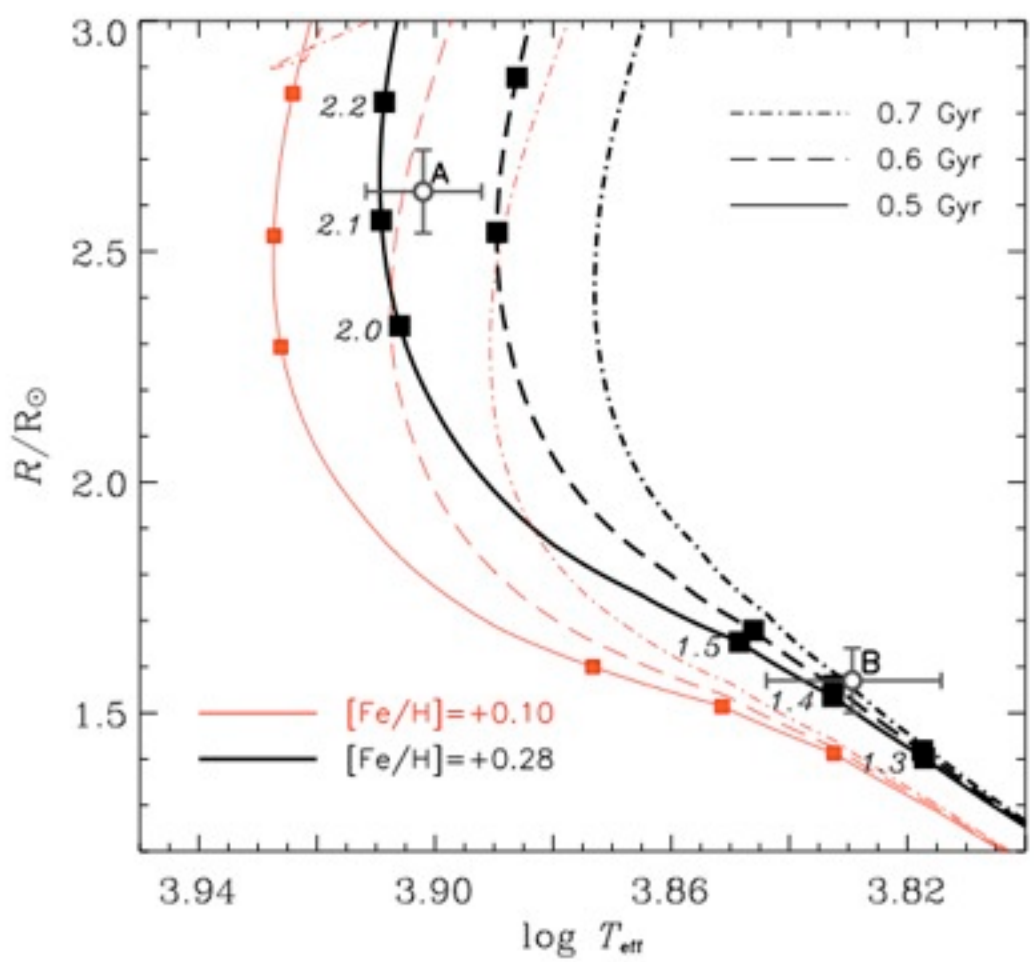


Fig. 3. Radius–T_{eff} diagram showing the location of the two components of β CrB. The thin lines are BASTI isochrones for [Fe/H] = +0.10 for ages 0.5, 0.6 and 0.7 Gyr. The thick lines are for the sames ages but for higher metallicity [Fe/H] = +0.28. On some of the isochrones the box symbols mark the masses at 1.3–1.5 $M_\odot$ and 2.0–2.2 $M_\odot$ in steps of 0.1 $M_\odot$.

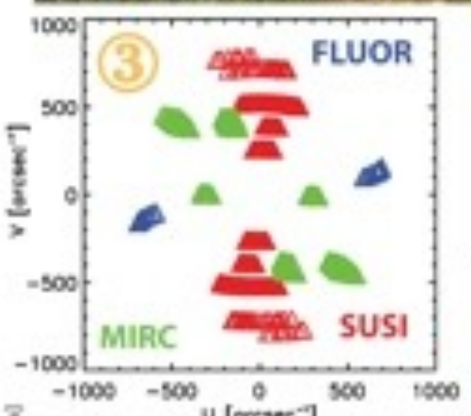
- Diameter of ***β*** *CrB A* measured by CHARA/ FLUOR (0.699 ± 0.017 mas)
- Data combined with VLT/ NACO AO imagery for photometry
- Improved T_{eff} calibration helps interpretation of asteroseismology data

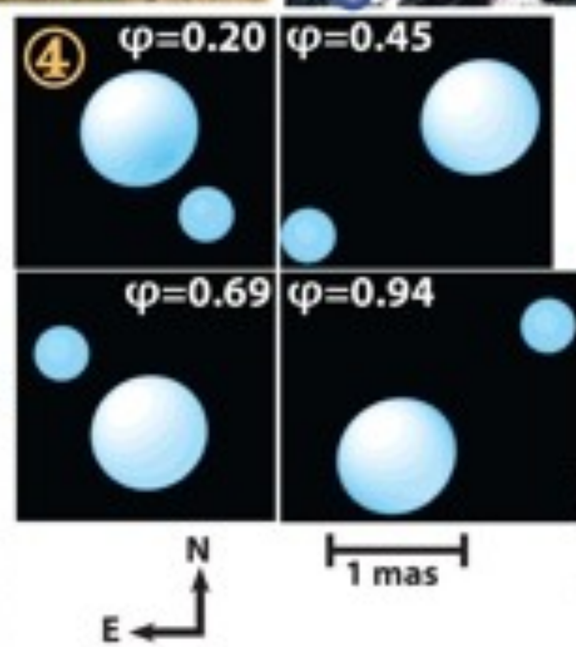
Spica
α Vir HR 5056

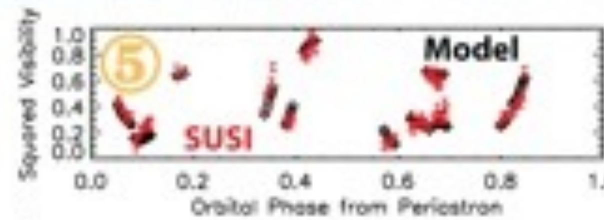
The Interferometric Orbit and Fundamental Parameters from the CHARA and SUSI Arrays

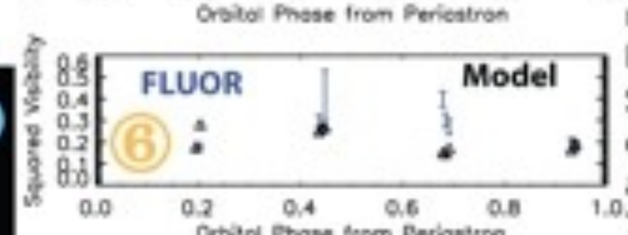
J. P. Aufdenberg[1], M. Ireland[2], A. Mérand[3], J. Monnier[4], M. Zhao[4], E. Pedretti[5], N. Thureau[5], S. Ridgway[6], V. Coudé du Foresto[7], W. Bagnuolo[8], D. Gies[8], T. ten Brummelaar[9], H. McAlister[8], J. Sturmann[9], L. Sturmann[9], N. Turner[9], A. Jacob[2], R. Riddle[10], B. Shah[1]

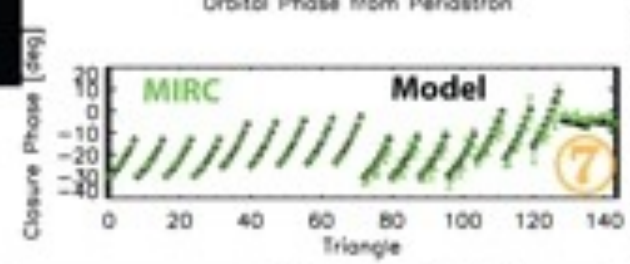
[1]Embry-Riddle Aeronautical University, [2]University of Sydney, Australia, [3]ESO, [4]University of Michigan, [5]University of St. Andrews, [6]NOAO, [7]LESIA, Observatoire de Paris, [8]Georgia State University, [9]CHARA Array, [10]Thirty Meter Telescope Corp.

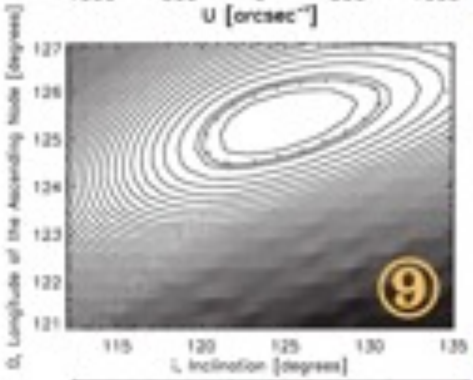


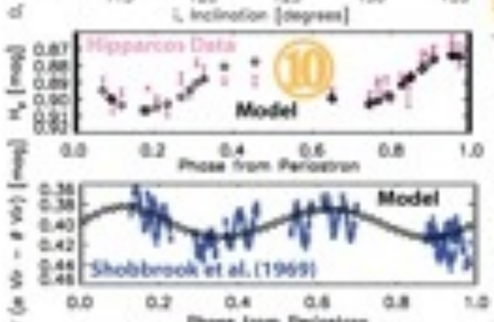












8

Parameter	Our Solution: Primary Component	Our Solution: Secondary Component	Herbison-Evans et al. (1971): Primary Component	Herbison-Evans et al. (1971): Secondary Component
Mass ($M_\odot$)	10.25±0.68	6.97±0.46	10.9±0.9	6.8±0.7
π_{orb} (mas)	11.75±0.25		11.90±0.57	
a (10^{12} cm)	1.91±0.02		1.93±0.06	
e	0.067 (fixed)		0.146 (fixed)	
i (deg)	126±6		65.9±1.8	
Ω (deg)	125.3±1.5		131.6±2.1	
$Radius_{pole}$ ($R_\odot$)	7.40±0.56	3.64±0.28	8.1±0.5	···
T_{eff}^{pole} (K)	24750±500	22500±500	22400± 1000	···
log(g) (cm s^{-2})	3.71±0.06	4.16±0.05	3.7±0.1	···
M_2/M_1, q	0.68±0.04		0.624±0.082	
a (mas)	1.50 ±0.036		1.54±0.05	
ω at T_0 (deg)	140±10		138±15	
Apsidal Period, U (years)	130±8		124± 11	

Spica, the close (85 pc), short-period (4.01 days), massive (10 $M_\odot$ + 7 $M_\odot$), eccentric (e = 0.07), and asynchronous binary star system, has been observed with the Sydney University Stellar Interferometer (SUSI) ① (at λ=700 nm) and the Center for High Angular Resolution Astronomy (CHARA) Array's ② MIRC (at H-band) and FLUOR (at K-band) instruments at projected baselines up to 310 m with spatial frequency coverage shown in ③.

A detailed binary model, following Wilson (1979), which includes the effects of tidal and rotational distortions ④ has been fit to these data. The best-fit model solution (χ_ν = 4.2) to the SUSI ⑤, FLUOR ⑥, and MIRC ⑦ data sets plus optical and near-IR spectrophotometry yields the orbital and physical parameters listed in the table ⑧.

The masses for the components, 10.3±0.7 $M_\odot$ and 7.0±0.5 $M_\odot$, are consistent with the masses from Herbison-Evans et al. (1971) based on observations from the Narrabri Stellar Intensity Interferometer. Effective temperatures, surface gravities, and radii are all consistent with the spectroscopic analysis of Lyubimkov et al. (1995).

Significant differences from the 1971 solution include a lower eccentricity (0.07 vs. 0.15), a lower inclination (54°±6° vs. 66°± 2°), and smaller longitude of the ascending node (125°±2° vs. 132°±2°). These last two parameters are provided only from interferometric observations. A least-squares surface ⑨ provides an estimate of these parameters' uncertainties.

Archival ellipsoidal photometric variations ⑩ are well represented by our distorted binary model. The model does not include the 4-hour variations due to non-radial pulsations.

The "observed" apsidal constant and the apsidal constant predicted by stellar structure computations remain discrepant for Spica. The observationally constrained value of the constant, $\log(k_{2\,obs})$ = -2.60±0.06, indicates a more centrally condensed primary star than predicted by Claret & Gimenez (1993), $\log(k_{2\,theo})$ = -2.40±0.03. The constant $k_{2\,obs}$ may be biased by reflection and non-Roche geometry effects not in our model.

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2009 science papers

- Refereed
  - Bruntt, H., et al. 2009. *The radius and effective temperature of the binary Ap star beta CrB from CHARA/FLUOR and VLT/NACO observations*. To appear in Astronomy & Astrophysics (ArXiv e-prints arXiv:0912.3215).
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- Other
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In writing (submitted 2010)

- Aufdenberg et al. Spica paper
- Mérand et al. eta Aql paper
- Di Folco et al. debris disks statistics
- Absil et al. dust properties

Perspectives

- A transition year
  - Consolidating on 2008 data
  - Several months lost due to broken fiber & fires
- Integrating FLUOR with other instruments is the way to go
  - FLUOR as a «fringe tracker» to VEGA
  - Checking asymetries with MIRC
  - Stabilizing FLUOR phase with CHAMP
  - More generally, joining interferometry with other techniques is the way to go
- 5-10 more years of unique science

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