FLUOR Science
Recent results, ongoing projects

V. Coudé du Foresto, O. Absil, **E. Di Folco**, P. Kervella, A. Mérand,
+ CHARA team !
+ J.-C. Augereau, D. Defrère, F. Thévenin + …

FLUOR science papers since last CHARA Meeting (2007-2009)

- **Akeson**, R. L., D. R. Ciardi, R. Millan-Gabet, A. Mérand, E. Di Folco, and 9 colleagues 2009. **Dust in the inner regions of debris disks around a stars**. Astrophysical Journal 691, 1896-1908.

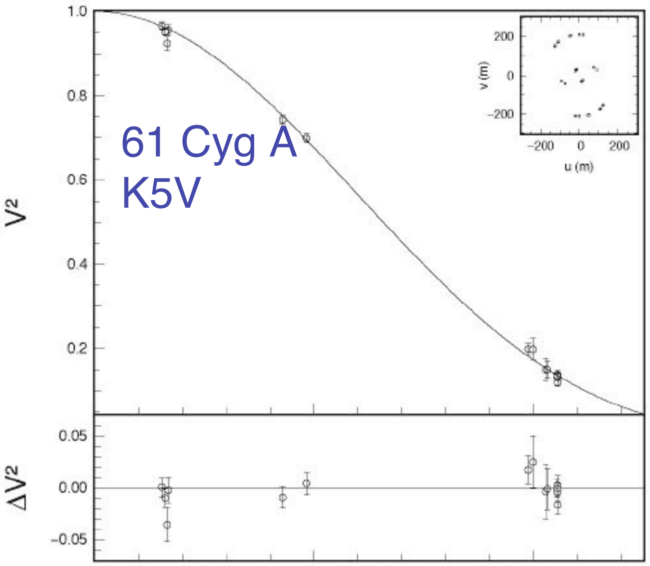
- **Kervella**, P., A. Mérand, B. Pichon, F. Thévenin, U. Heiter, and 9 colleagues 2008. **The radii of the nearby K5V and K7V stars 61 Cygni A & B**. CHARA/FLUOR interferometry and CESAM2k modeling. Astronomy and Astrophysics 488, 667-674.

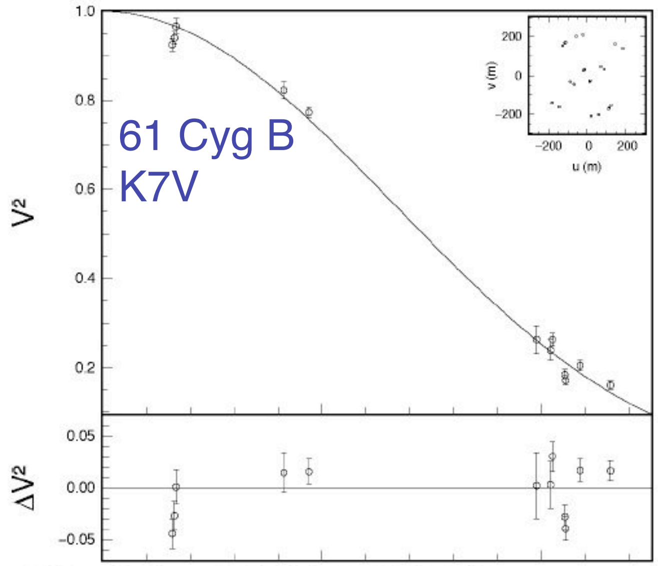
- **Absil**, O., E. Di Folco, A. Mérand, J.-C. Augereau, V. Coudé Du Foresto, and 13 colleagues 2008. **A near-infrared interferometric survey of debris disc stars. II. CHARA/FLUOR observations of six early-type dwarfs**. Astronomy and Astrophysics 487, 1041-1054.

- **Di Folco**, E., O. Absil, J.-C. Augereau, A. Mérand, V. Coudé Du Foresto, and 9 colleagues 2007. **A near-infrared interferometric survey of debris disk stars. I. Probing the hot dust content around epsilon Eridani and tau Ceti with CHARA/FLUOR**. Astronomy and Astrophysics 475, 243-250.

- **Mérand**, A., J. P. Aufdenberg, P. Kervella, V. C. d. Foresto, T. A. ten Brummelaar, and 4 colleagues 2007. **Extended Envelopes around Galactic Cepheids. III. Y Ophiuchi and alpha Persei from Near-Infrared Interferometry with CHARA/FLUOR**. Astrophysical Journal 664, 1093-1101.

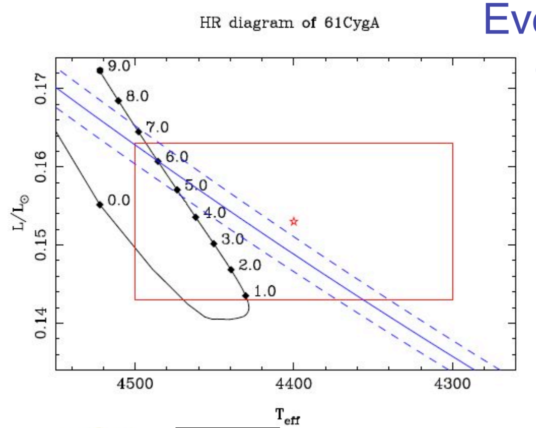
Topic 1: 61 Cyg A&B diameters and evolutionary status of asteroseismology targets (Kervella, Thévenin et al. 2008)

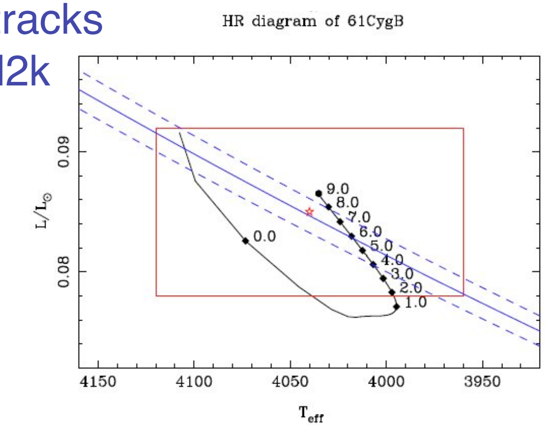




$\theta_{LD}(A) = 1.775 \pm 0.013$ mas and $\theta_{LD}(B) = 1.581 \pm 0.022$ mas.

Evolution tracks CESAM2k





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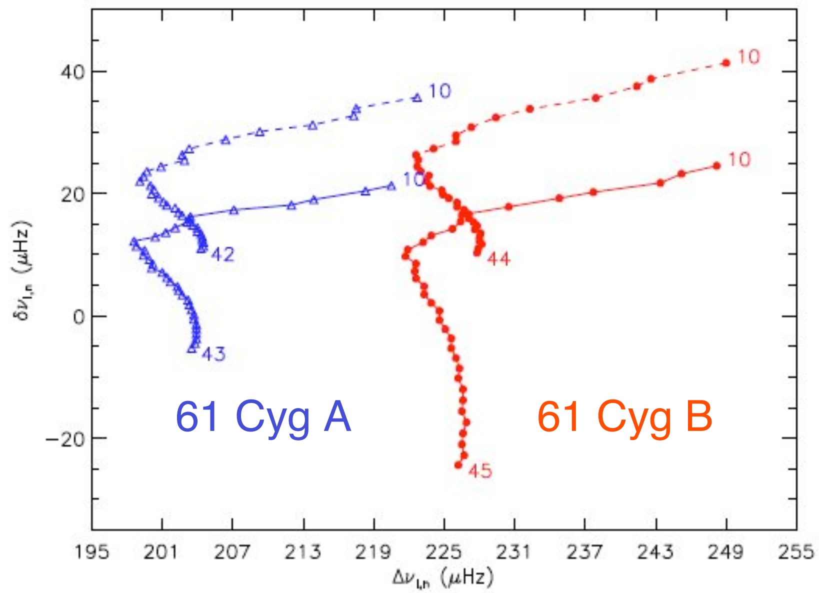
61 Cyg A & B: fundamental parameters

Parameter	61 Cyg A	61 Cyg B
π (mas)	286.9 ± 1.1	285.4 ± 0.7
[Fe/H]	-0.20 ± 0.10	-0.27 ± 0.19
$R(R_\odot)$	0.665 ± 0.005	0.595 ± 0.008
$T_{\rm eff}$ (K)	$4\,400 \pm 100$	$4\,040 \pm 80$
$L\,(L_\odot)$	0.153 ± 0.010	0.085 ± 0.007
Initial He content $Y_{\rm ini}$	0.265	0.265
Initial [Z/H] (dex)	−0.10	−0.10
Final [Z/H] (dex)	−0.15	−0.15
Age (Gyr)	6.0 ± 1.0	6.0 ± 1.0
Mass ($M_\odot$)	0.690	0.605
α (MLT convection)	1.2	0.8

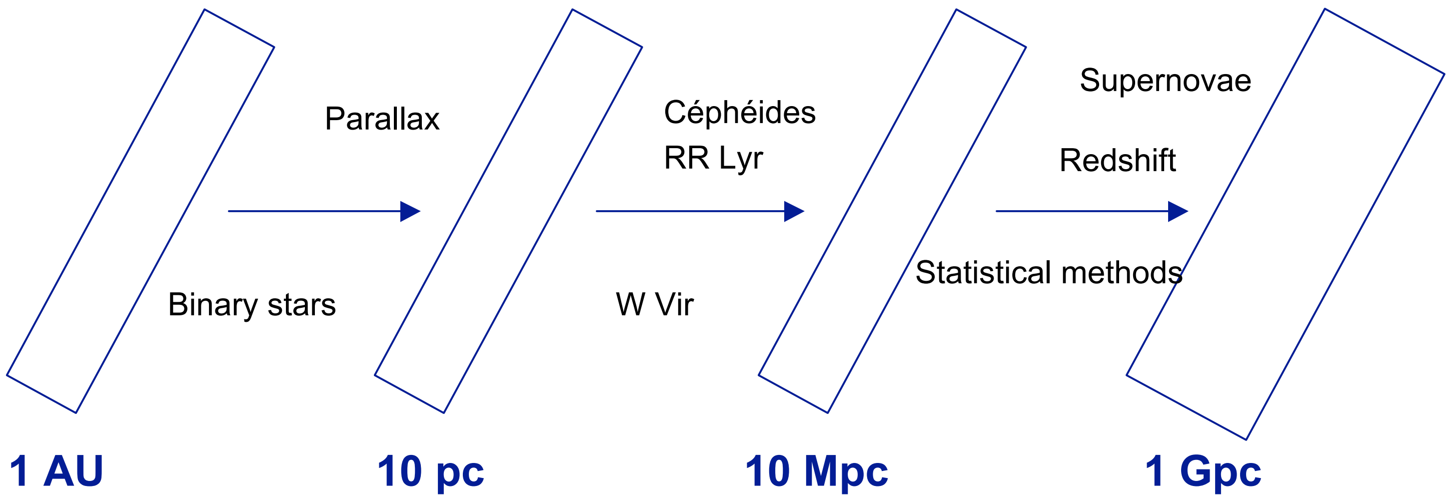
Prediction of asteroseismic observables
CESAM2k



Stellar atmosphere modeling constraints the age (6Gyr), mixing length
Asteroseismic observations => Small and large frequency separations
=> accurate **Masses** and evolutionary status

Topic2 - Cepheids: distance and envelopes

- A key-role in the determination of distances in the Universe



Calibrating the Period-Luminosity relationship

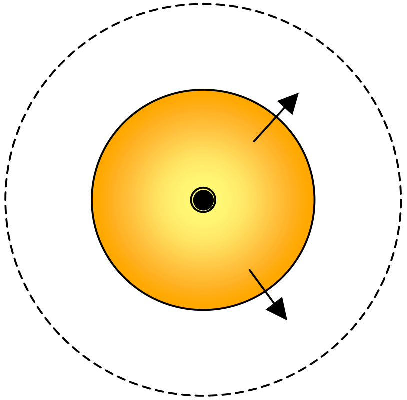
- ***Log (L)* = *a* . Log(*P*) + *b***
- The slope ***a*** is constrained (SMC, LMC)
- The ***zero-point b*** is the Graal
- Requires several independent measurements

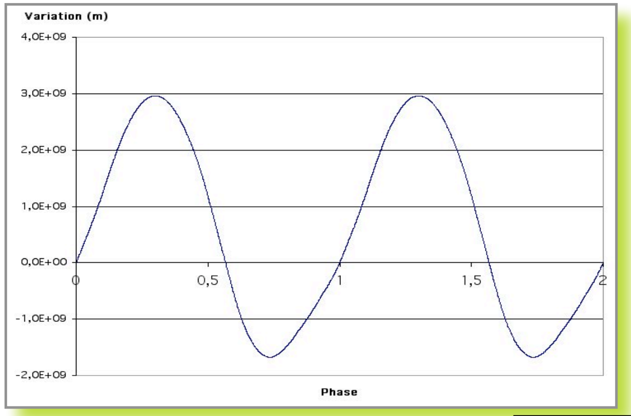
(a handful of high-precision observations of Cepheids with interferometry available today)

Typical precision achieved on b ~ 0.06 mag

Pulsation parallax method

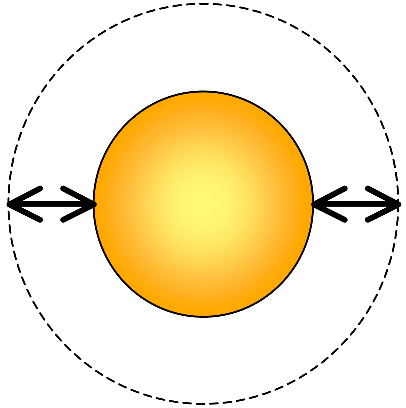
- Radial velocity monitoring

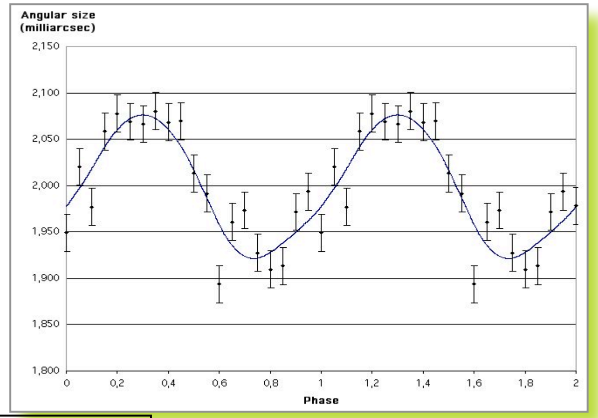




Pulsation along the line of sight

- Interferometry



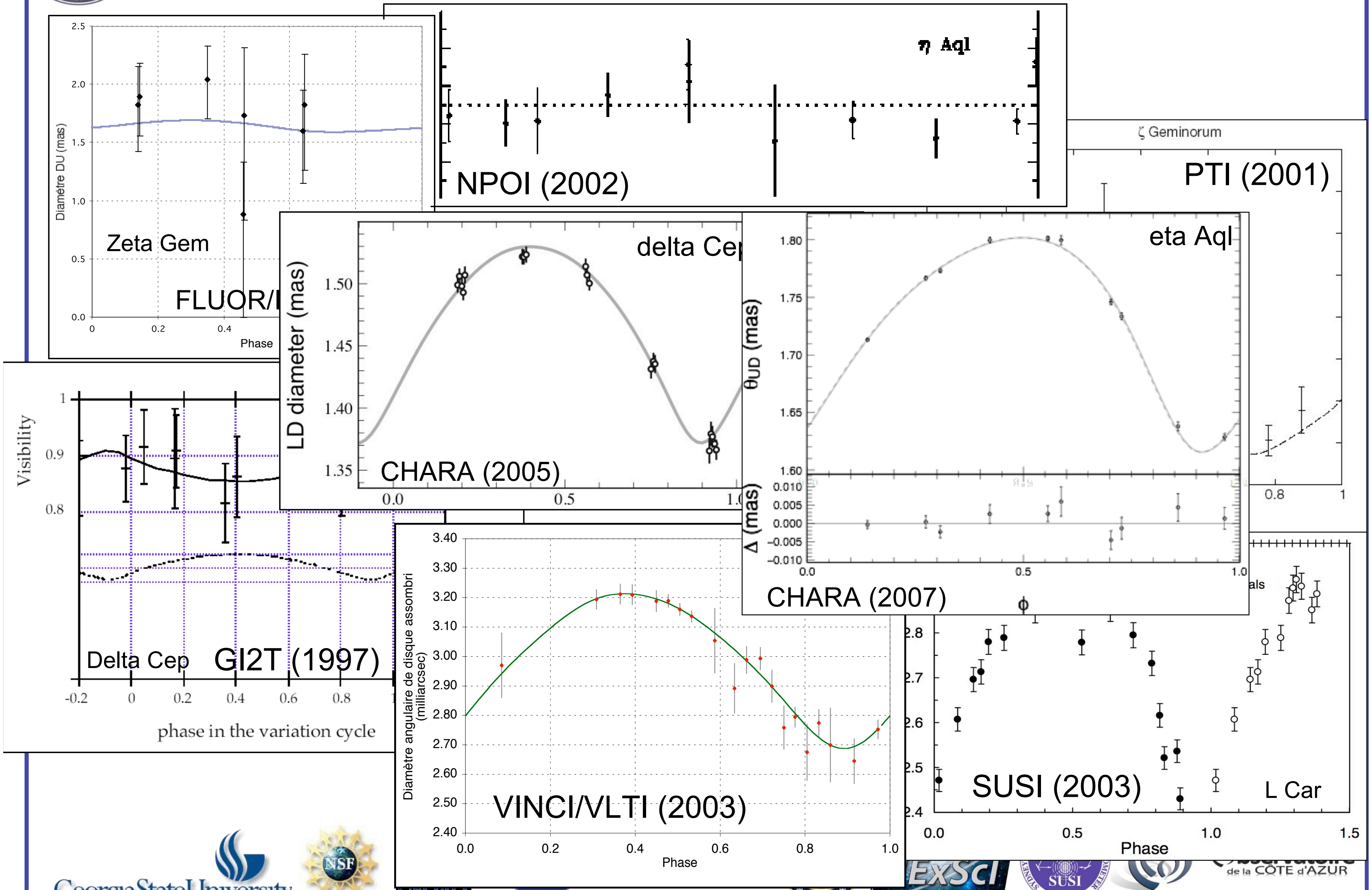


… and in the sky plane

Distance

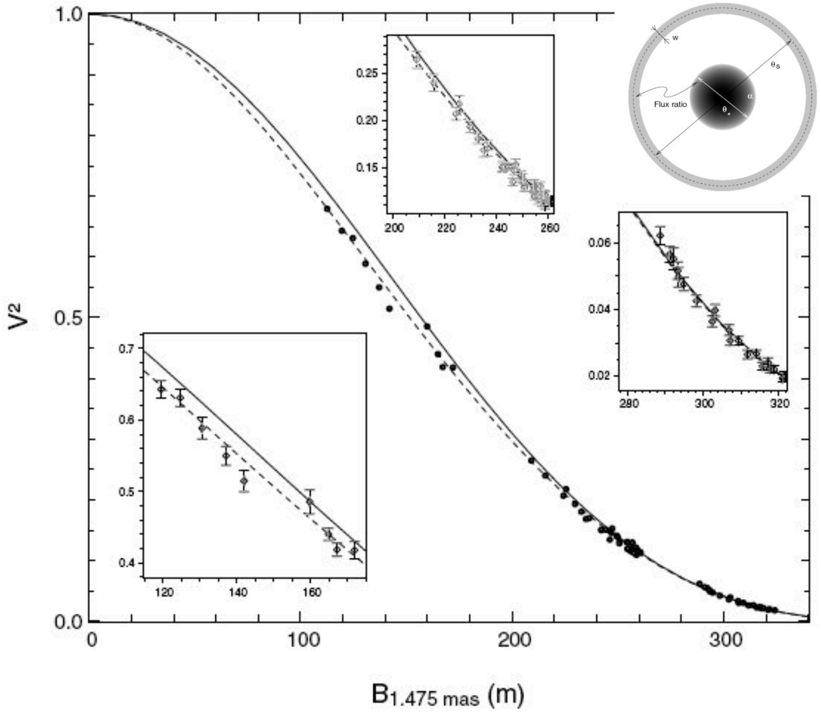
$$\theta_{\rm UD}(T) - \theta_{\rm UD}(0) = -2\,\frac{kp}{d}\int_0^T v_{\rm rad}(t)\,dt$$

Cepheids and Interferometry: 1997-2007



Cepheids: circumstellar envelopes

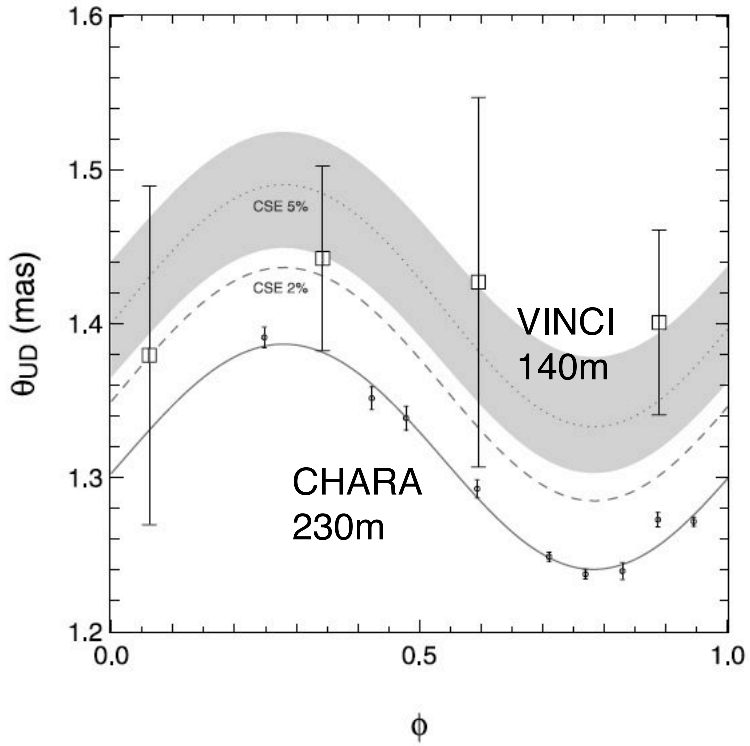
δ Cep (Mérand et al. 2006)



$R_{CSE} \sim 3\ R_{star}$

Bias = f(baseline length)

Y Oph (Mérand et al. 2007)

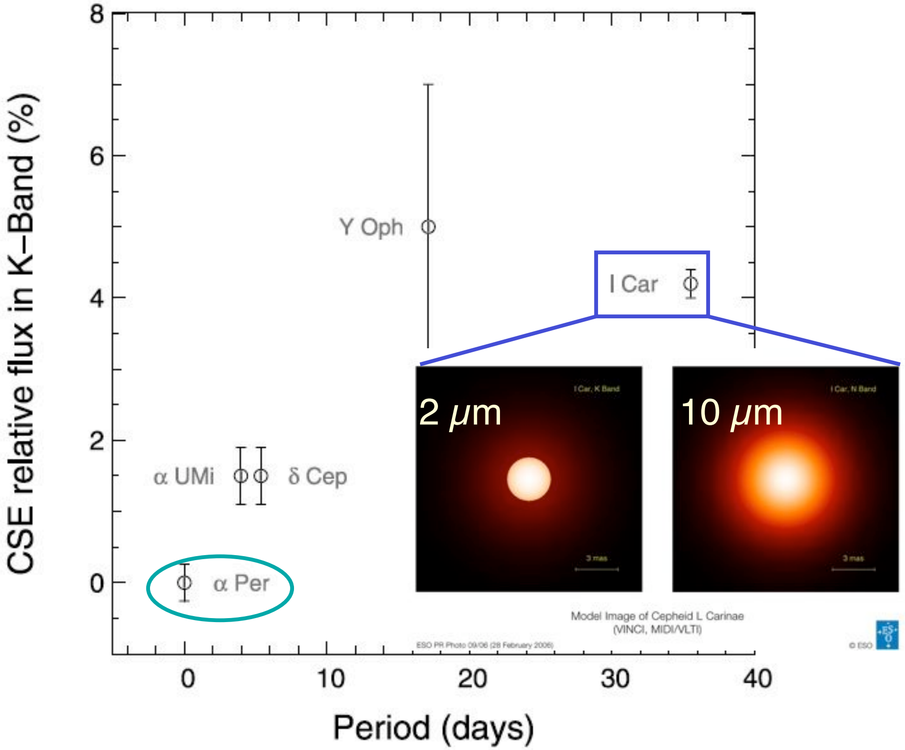


D = 472 ± 18 pc

D = 491 ± 18 pc unbiased (=4% !)

Cepheids: circumstellar envelopes

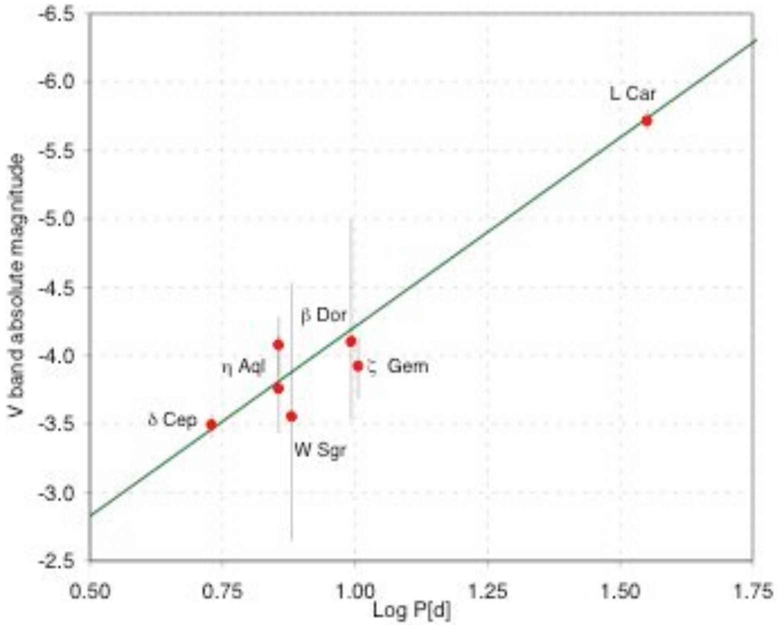
$Flux_{CSE}$ ~ 2-5%



Enveloppes found around 4/4 Cepheids …

Link with mass-loss, Correlation F_{CSE} vs. Period ?

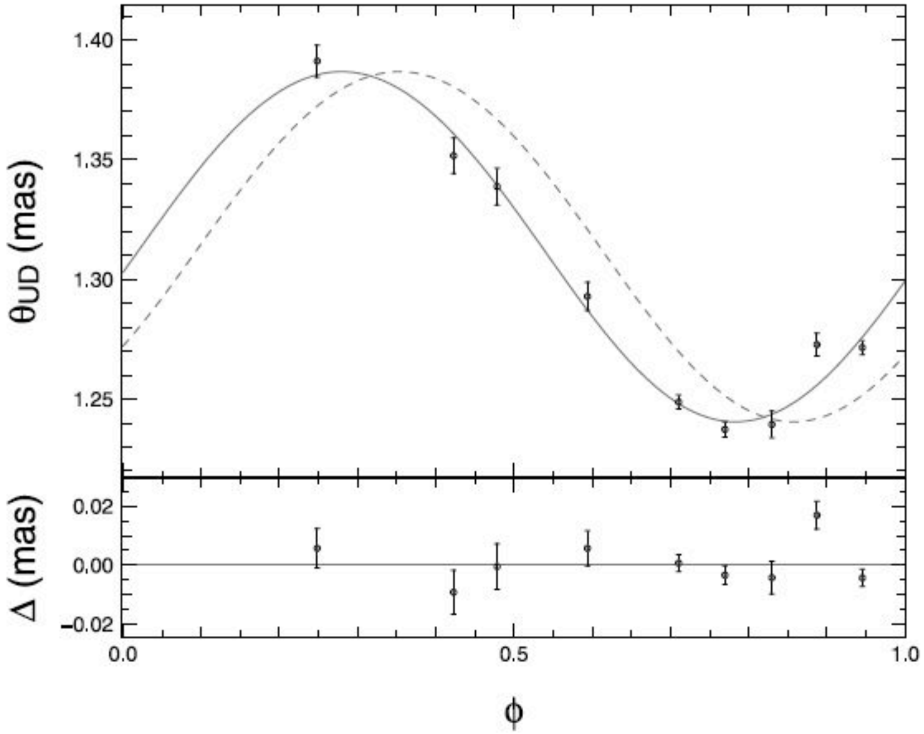
Period-Luminosity relationship



Adapted from Kervella 2004, after debiasing for CSE

Cepheids: distance and envelopes

Y Oph (Mérand et al. 2007)



Y Oph = low-amplitude Cepheid, P~17d
(crossing the instability strip for 3rd time)

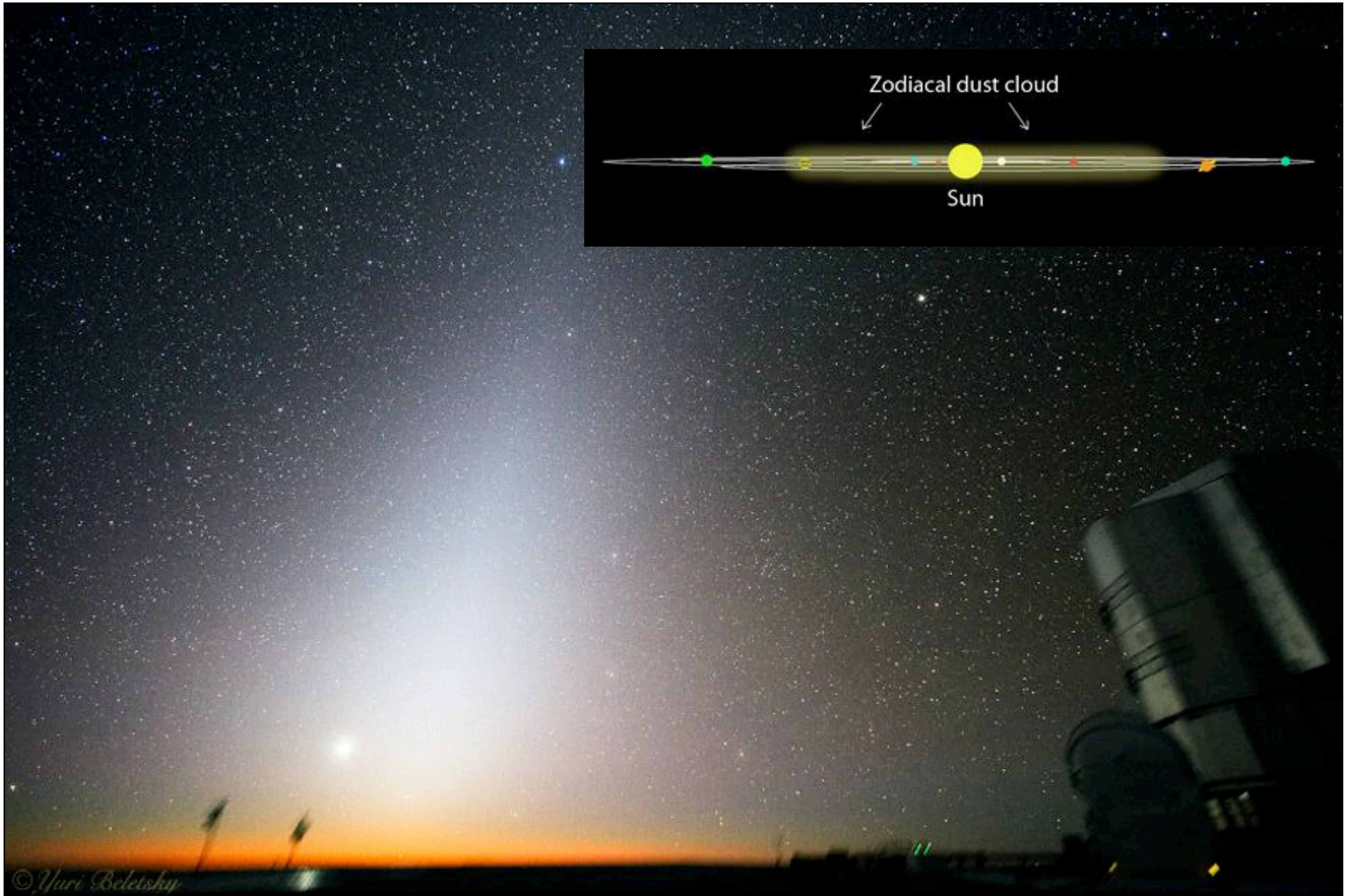
Derived Linear radius:
R = 67.8 ± 2.5 R_0
Expected from P-R relationship:
R = 100 ± 8 R_0 !

Y Oph :
- probably not a fundamental-mode pulsator
- shows phase-shift (1d) between RV and angular diameter variations…

=> should be excluded from P-L calibration

More to come: the most precise distance estimation so far for a Cepheid (Mérand et al. 2009 in prep)

Topic 3   Exozodiacal disks: the quest for hot dust



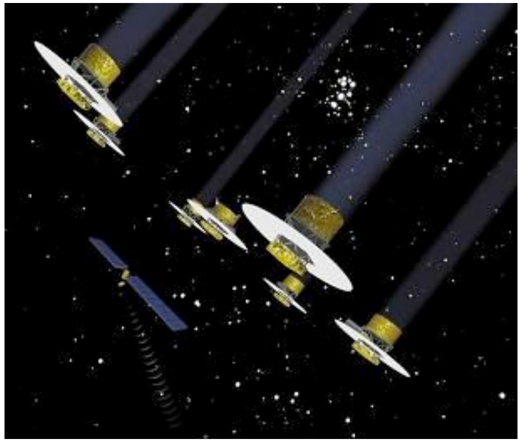
Why look for warm exozodi ?

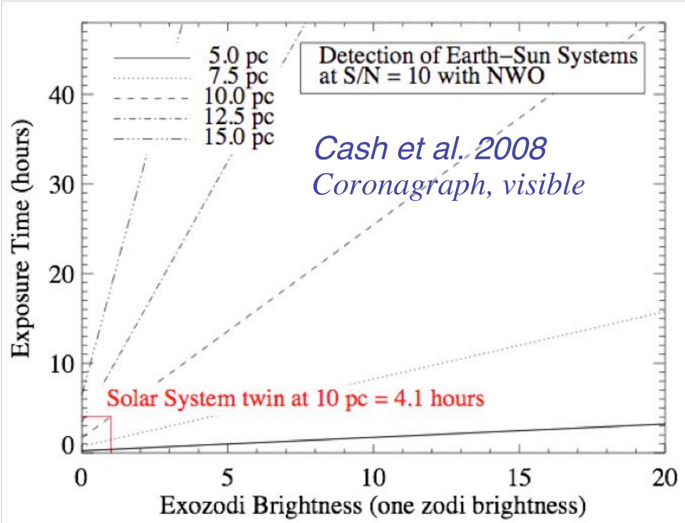
Dust grains distribution -> dynamics of the parent bodies

How common is our own solar system ?
How do planetary systems evolve ?

Requires information on :
- morphology of dust exo zodi
- composition of dust (multi-λ)

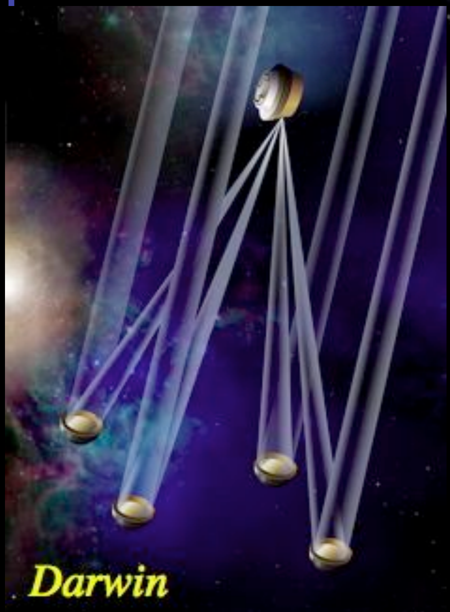
Prepare future missions to directly detect earth-like planets
TPF-like missions -> Feasibility ? Target selection ?

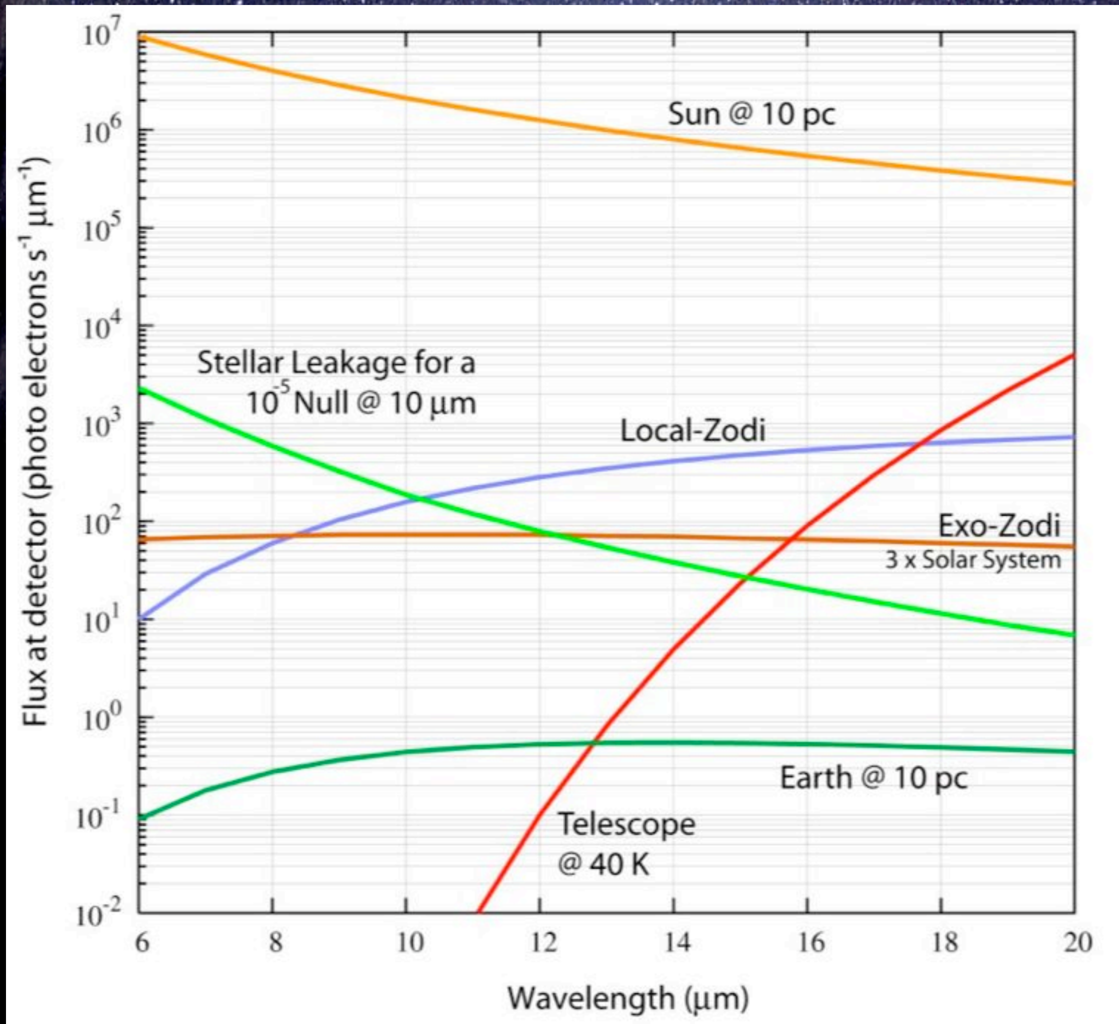




CHARA Collaborati

Exozodiacal light as an «issue»





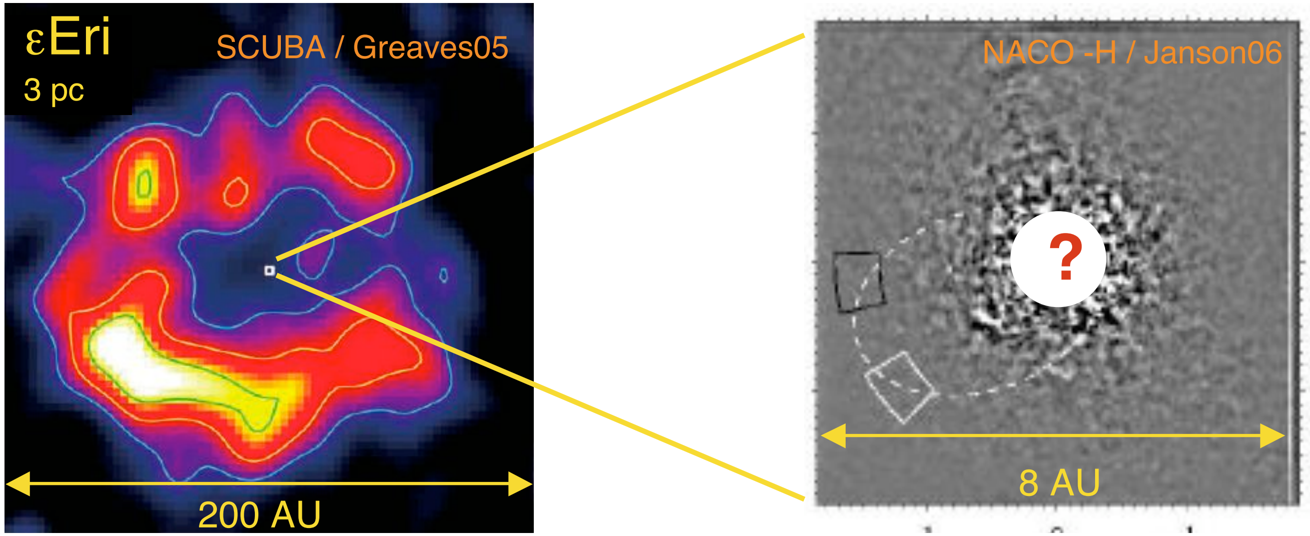
Source: DARWIN CV proposal

The quest for exo-zodiacal warm dust

Spitzer photometry (Trilling 07, Bryden 06, Beichman 06, Chen 06)

- Positive detections < 2.5% of 1-10Gyr GK stars @10 μm
  4%@24mic, 16%@70μm.
- Sensitivity threshold ~ 1000 Zodi $8 < \lambda < 24$ μm
- Absolute accuracy ~ 4% photospheric flux
- Statistics: majority of exozodii 0.1 zodi < Lum < 10 zodi

Direct Imaging



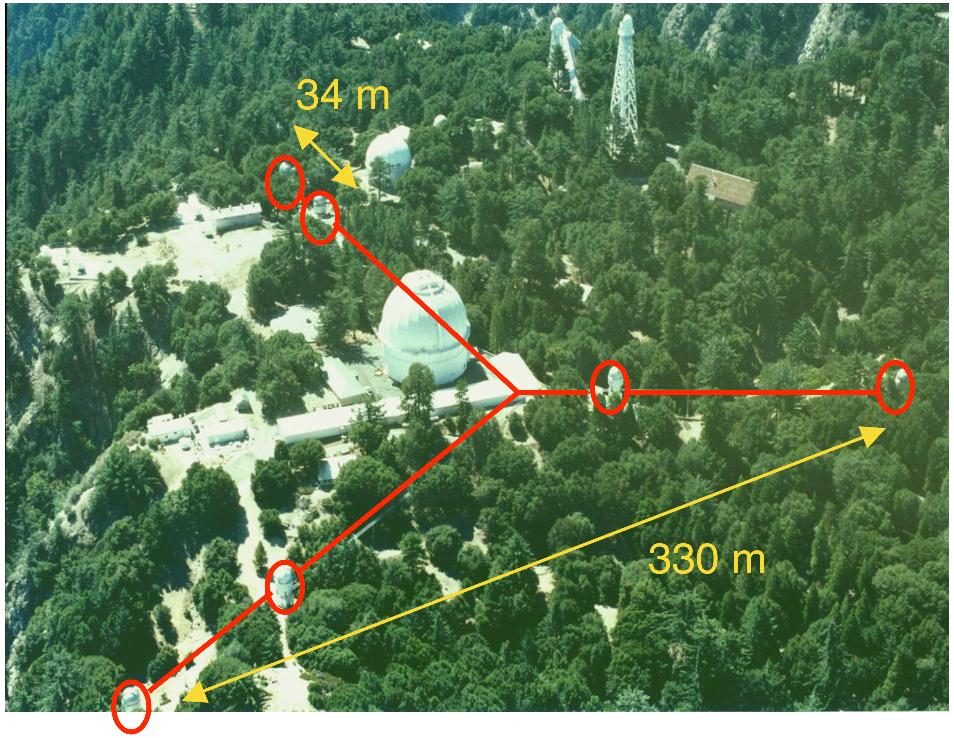
Needs: small FOV, high spatial resolution, high dynamics

A survey of debris discs with CHARA/FLUOR

CHARA Array (Mt Wilson, CA)
6 1m-telescopes

FLUOR instrument
2-T combiner, 2.2 μm fiber-filtered
high precision visibility

Strategy
Short 30m baseline (CSE)
Long (>200m) baseline (photosphere)



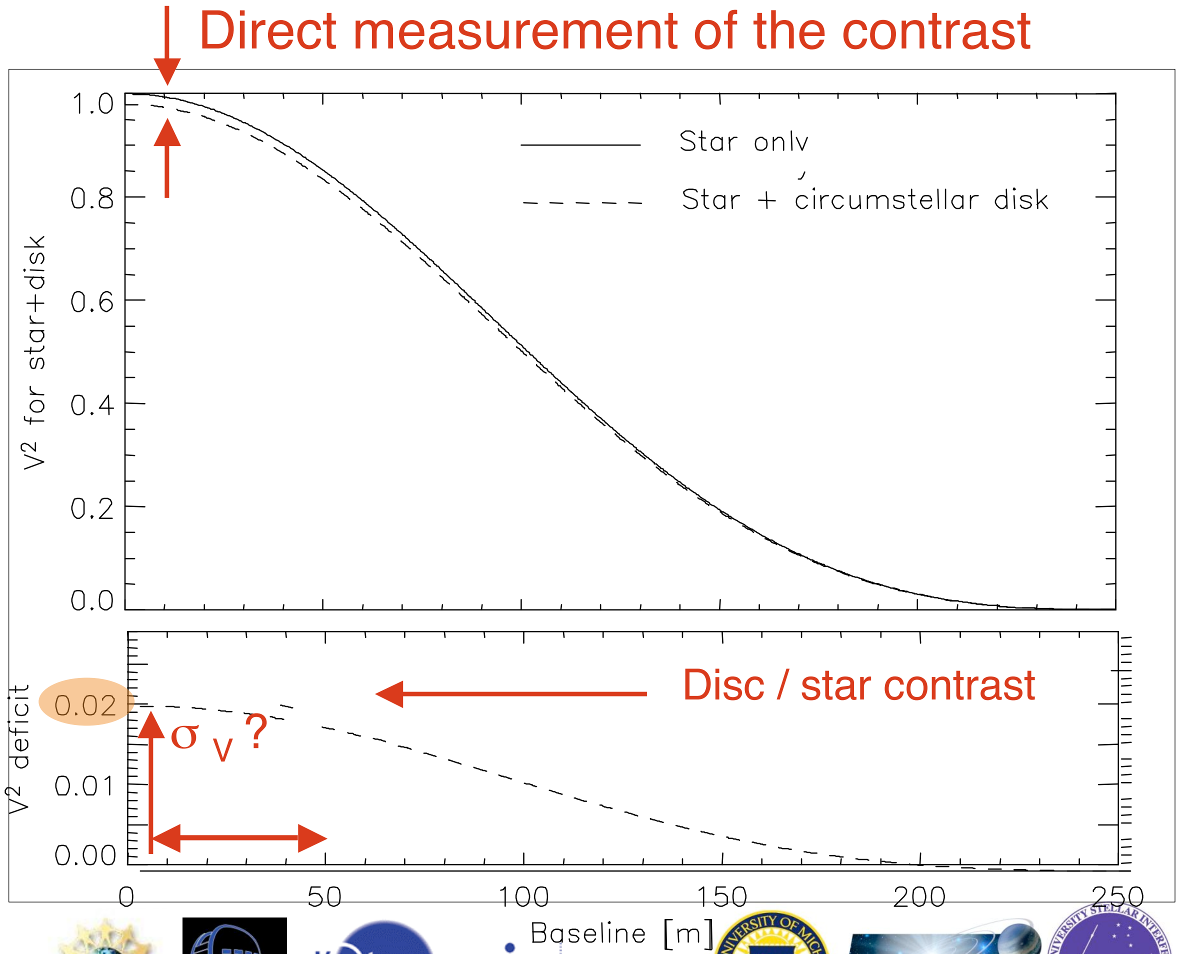
Survey of MS stars (K < 5) with known, cold debris discs

ϵ Eri K2V
τ Cet G8V
σ Boo η Crv F2V
β UMa A1V
Vega ζ Aql
α CrB γ Oph A0V

IR interferometry: towards high contrast imaging

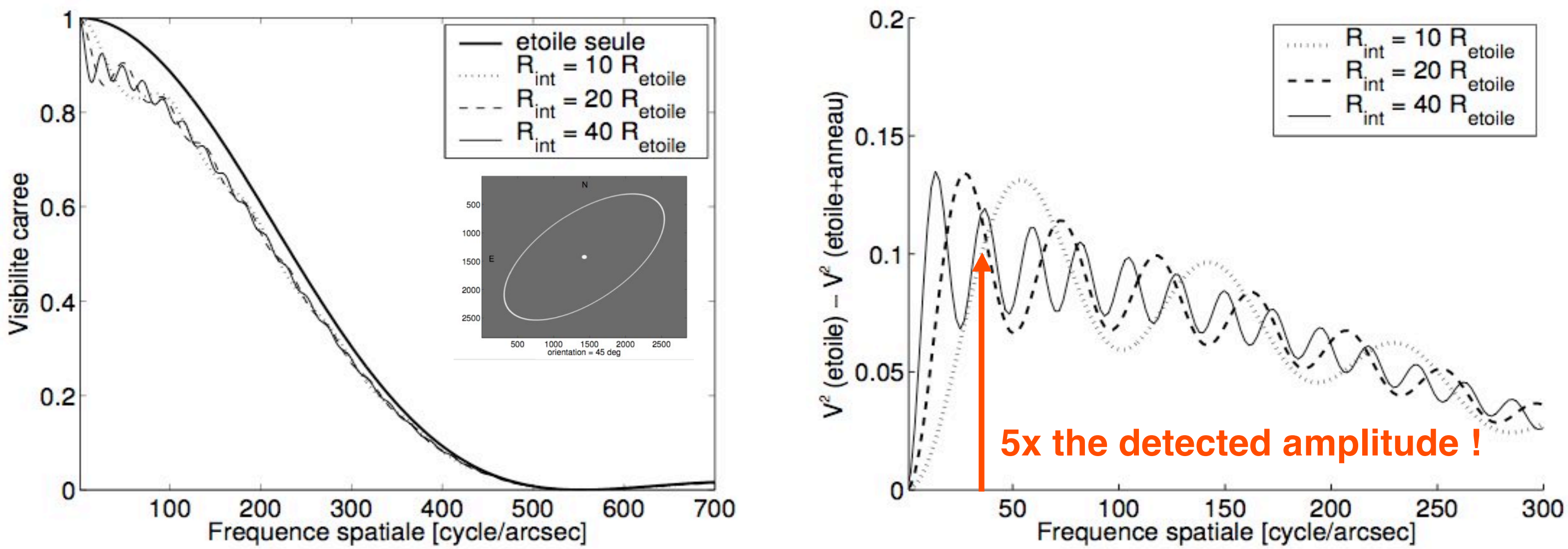
-> Rachel's talk
FLUOR FOV ~ 0.8 arcsec (few AU @ nearby stars)
Dusty disk extended emission induces a
Visibility drop, best detected at short baselines

Direct measurement of the contrast



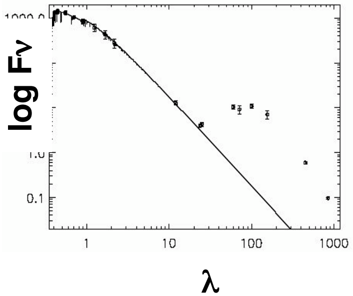
Constraining the morphology ?

- Lift modeling degeneracy through:
  - Spatial characterization (need fine (u,v) sampling)
  - Spectral characterization (FLUOR+prism; H band?)

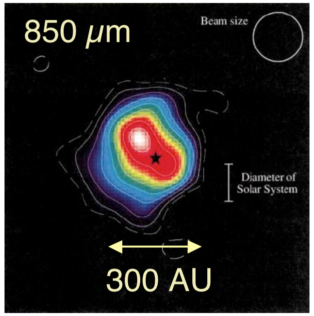


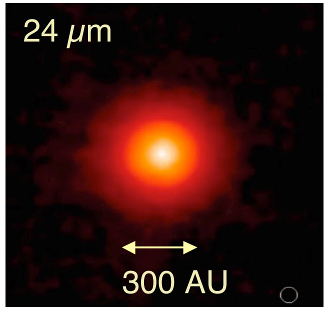
E. di Folco, PhD thesis (2004)

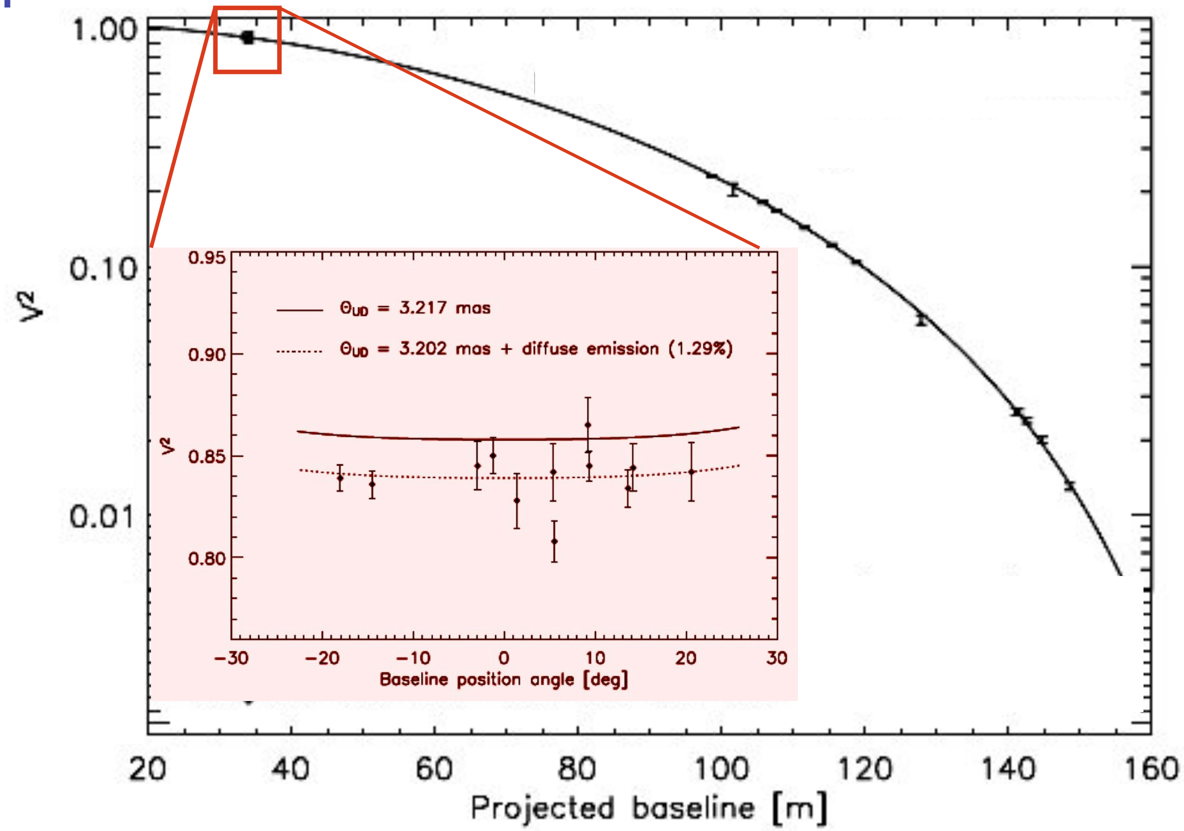
Vega: the first detection
Absil, Di Folco et al. 2006



Vega:
fast rotating A0V
7.7 pc ~300 Myr







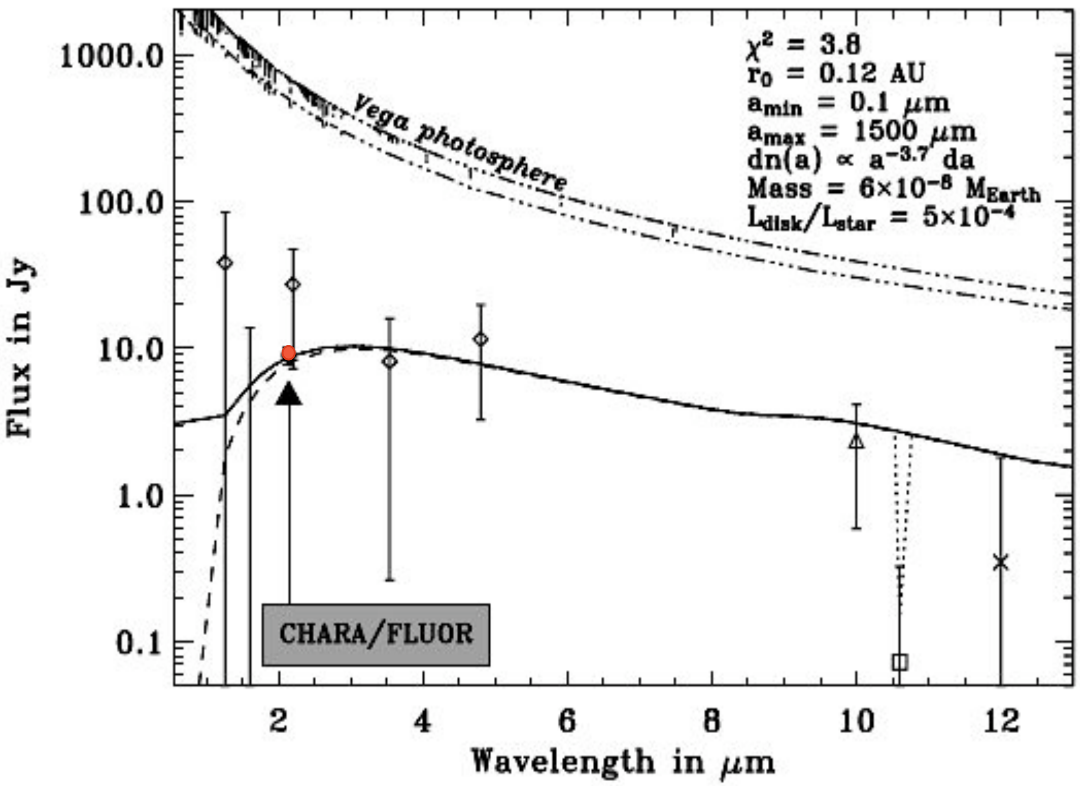
Detected excess:

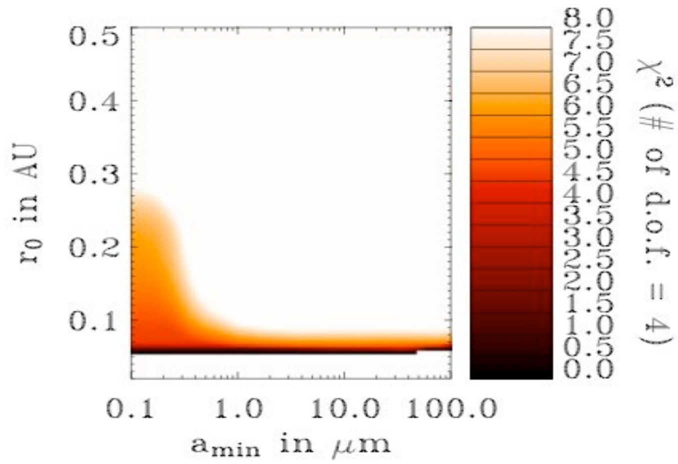
$f_K = 1.29 \pm 0.2\ \ 10^{-2}$

Origin:

- background object ?
- bound companion ?
- stellar wind ?
- hot dust grains ?

Vega: modeling the hot dust grains





Model Augereau (1999)

- ✓ Sub-micron grains
- ✓ Steep distribution close to sublimation distance
- ✓ Carbon/Si > 50%
- ✓ $M_{dust} \sim 10^{-8}\ M_{\oplus}$

Large amount of small grains: 10 Hale-Bopp comets/day !?

Origin? LHB-like phenomenon ? (see also Wyatt 07)

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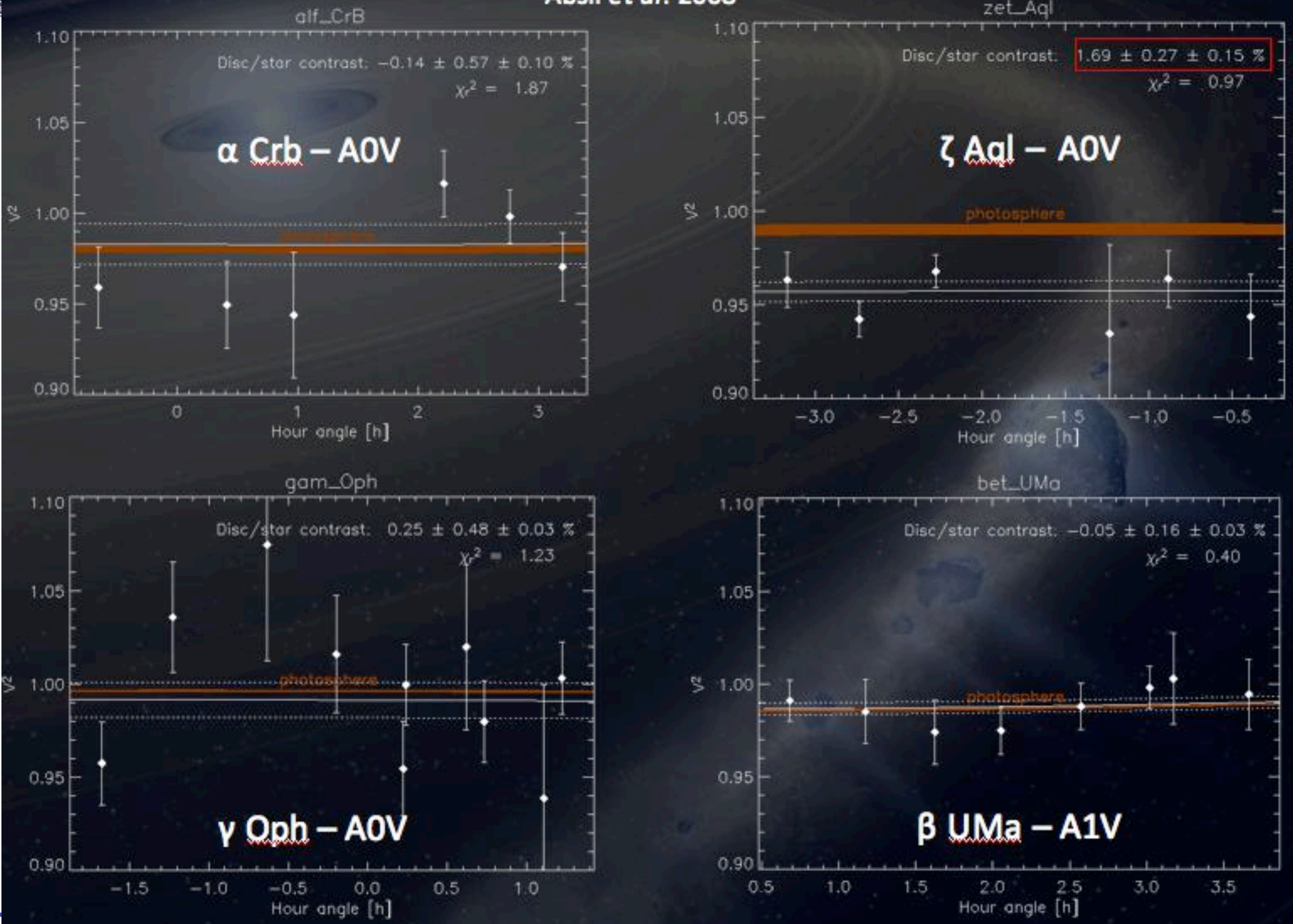
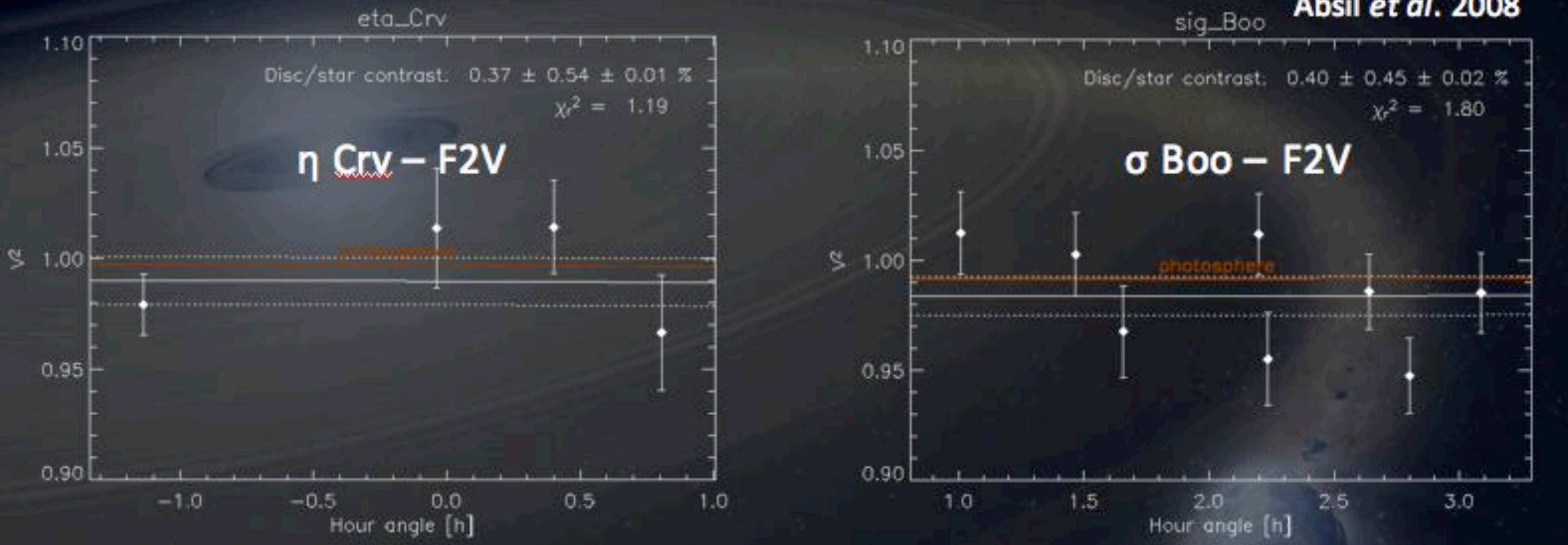
Hot stars program

Absil *et al.* 2008

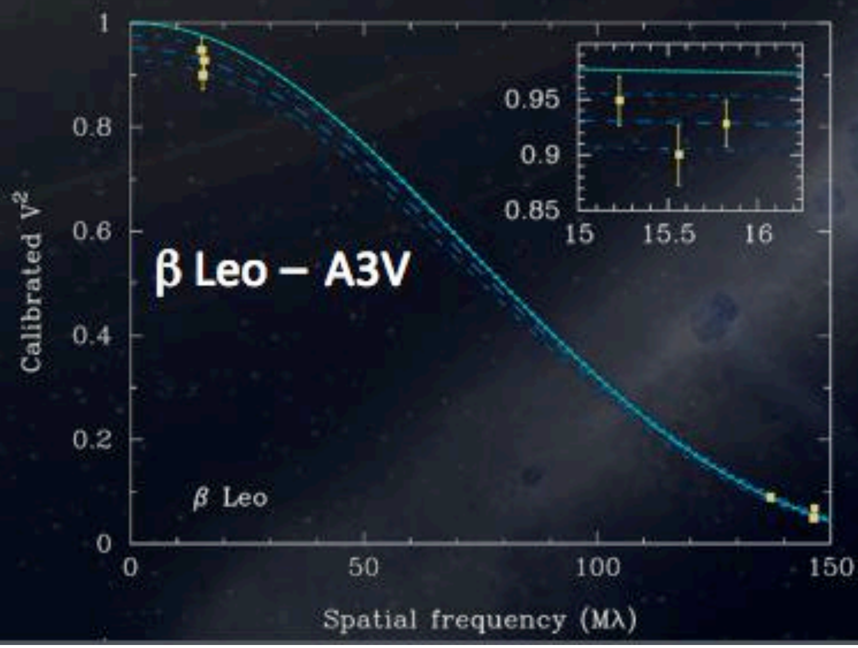


Hot stars program

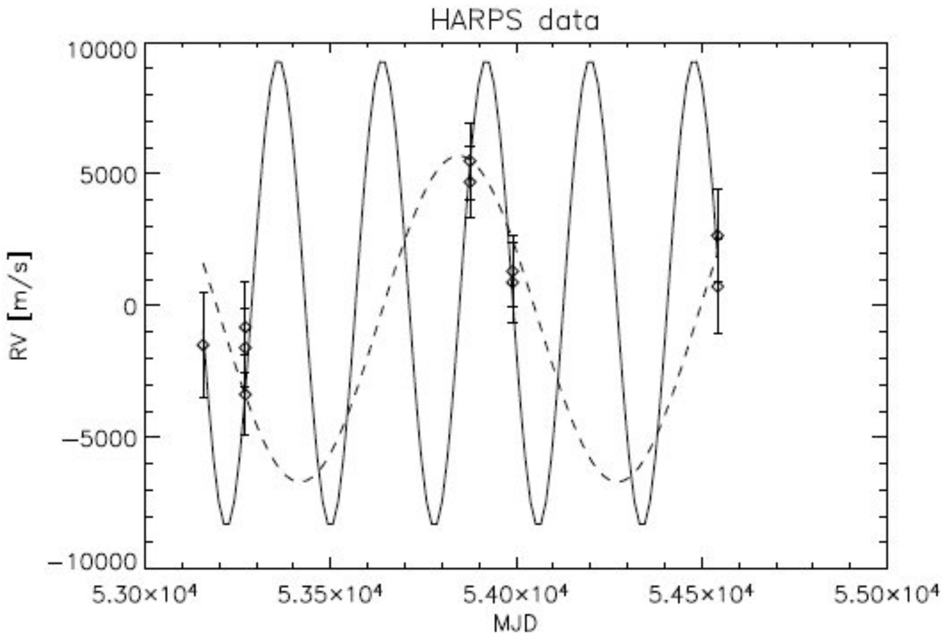
Absil *et al.* 2008

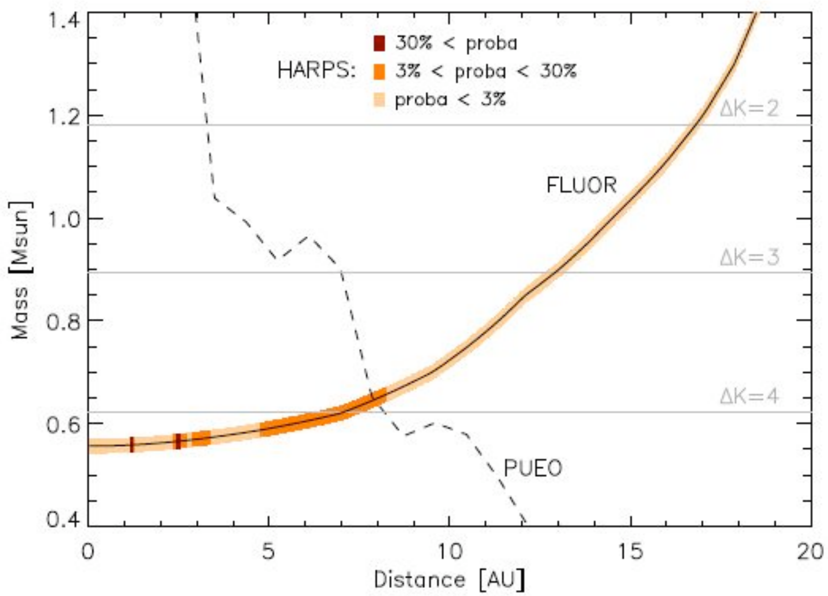


Akeson *et al.* 2009



Zet Aql: dust or low-mass companion ?
Complementary observations are crucial

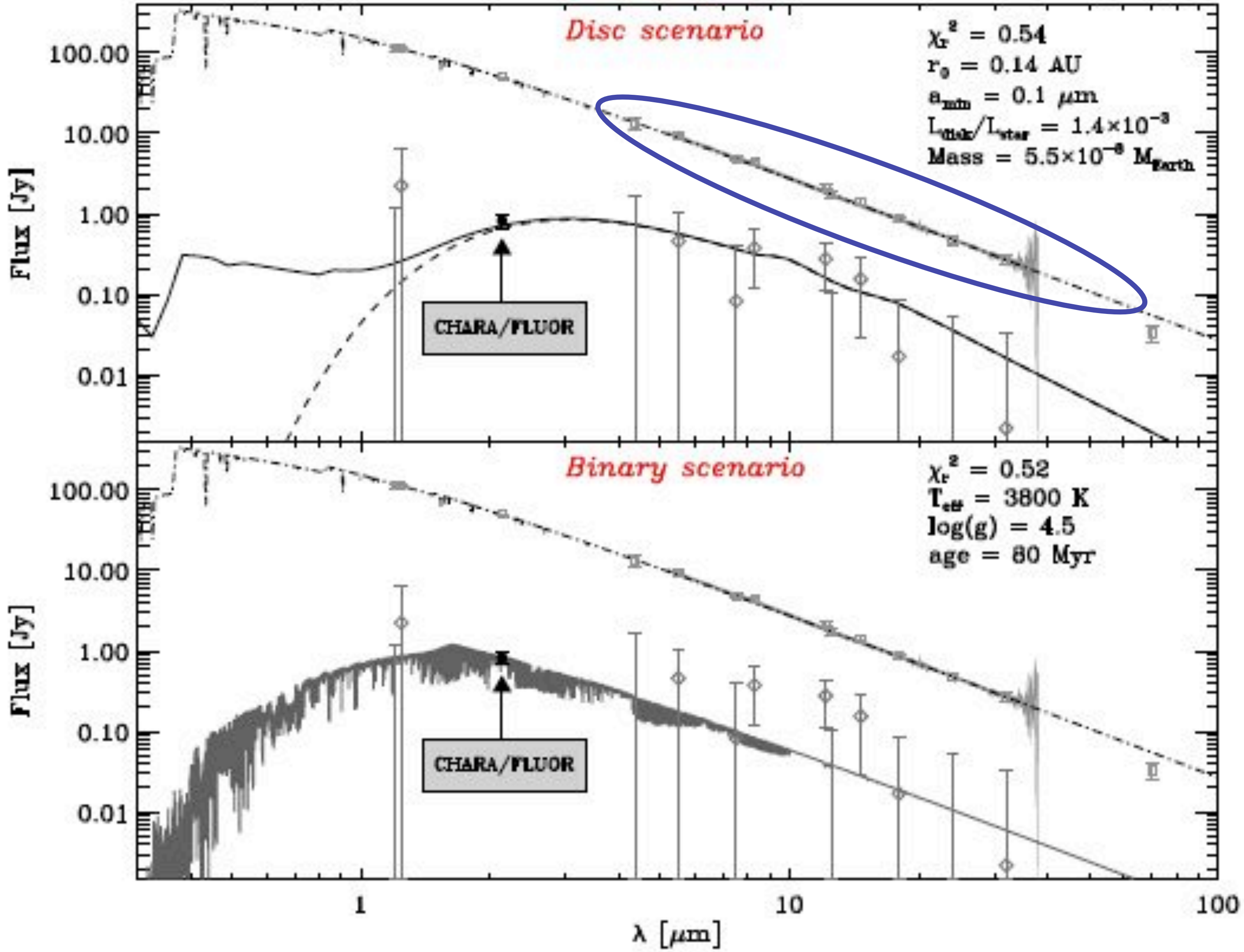




Not yet conclusive for this star !
Stronger constraints are needed…

Zet Aql: no more cold debris ?

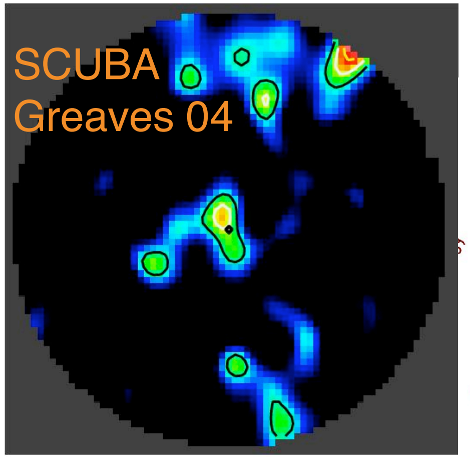
Re-analysis of Spitzer IRS+MIPS data (Chen06): no longer warm/cold excess !

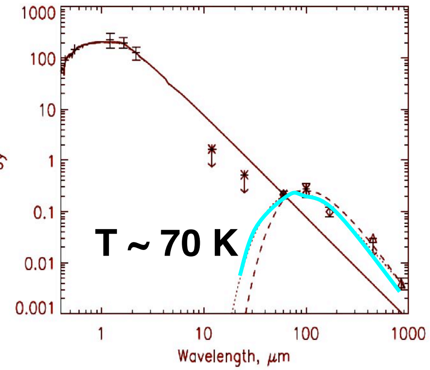


τ Ceti & ε Eridani: two sun-like stars

τ Ceti

G8V
3.6 pc, ~10 Gyr
RV stable over 6yr



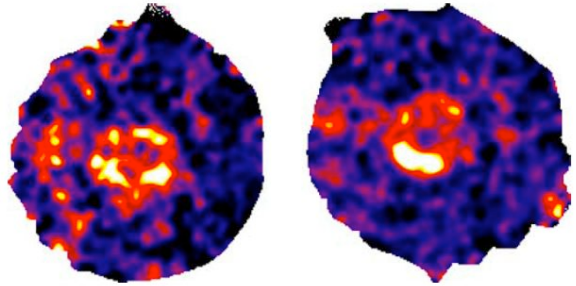


Spitzer 8-24 μm:
Consistent with photospheric (Chen et al. 06)

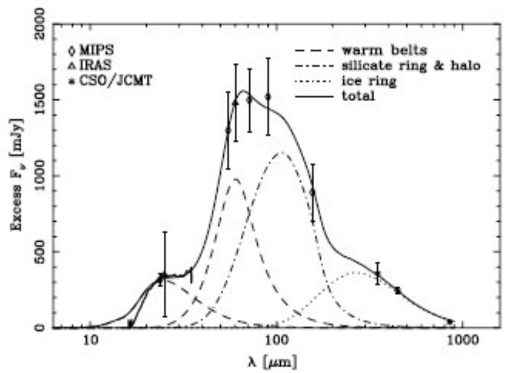
ε Eridani

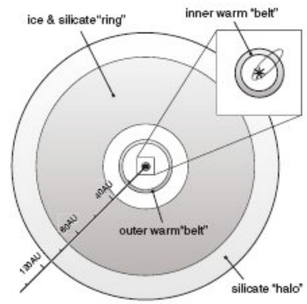
K2V (active)
3.2 pc, ~0.5 Gyr
+1 eccentric Jupiter (Hatzes00, Benedikt06)

SCUBA: resonant structures ? Poulton et al.06



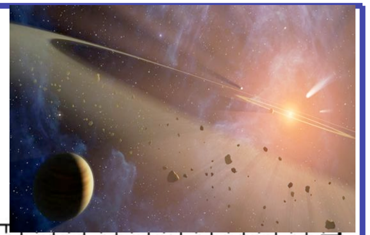
Spitzer: 3AU + 20AU asteroid belts
Backman et al 2009

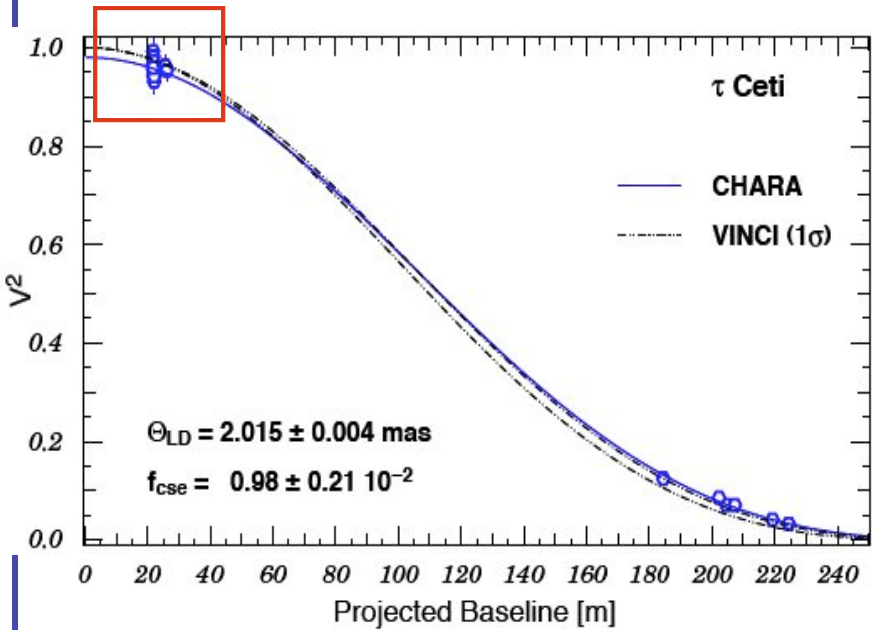


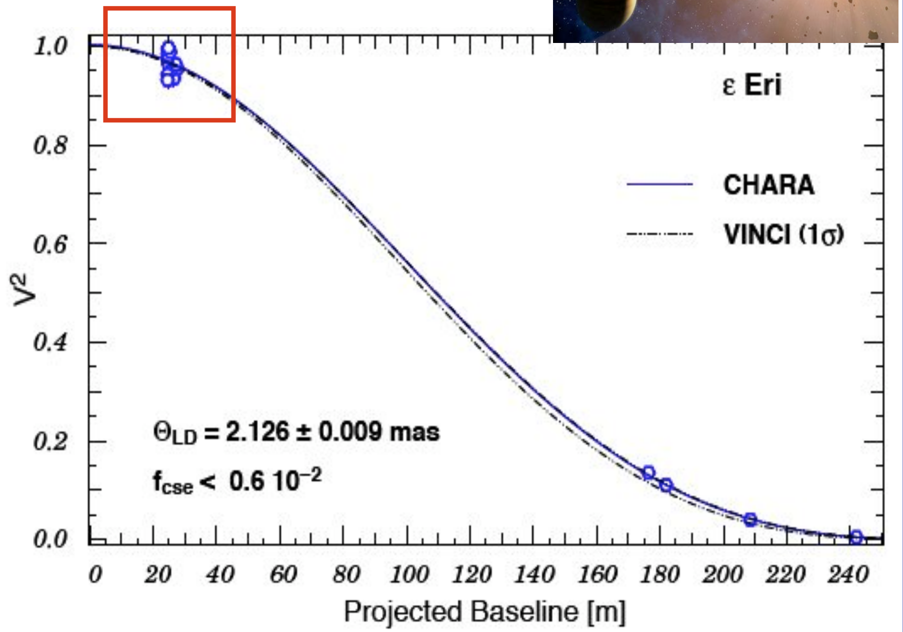


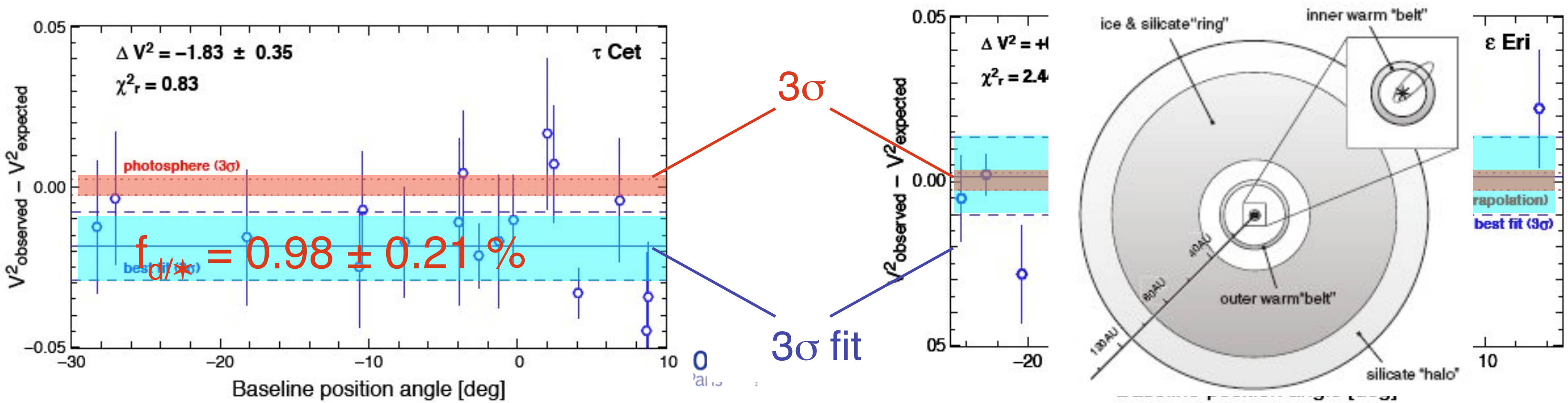
Hot zodiacal dust around τ Ceti

Di Folco et al. 2007

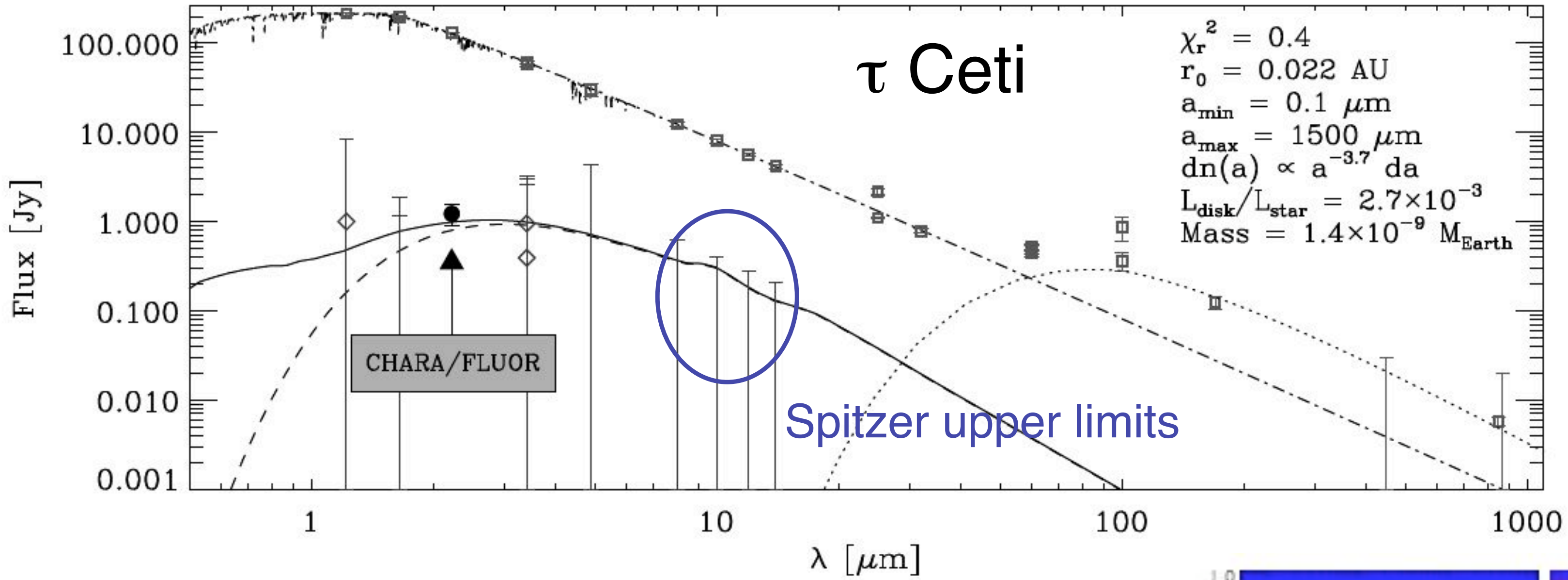








Dust properties: from observation to modeling



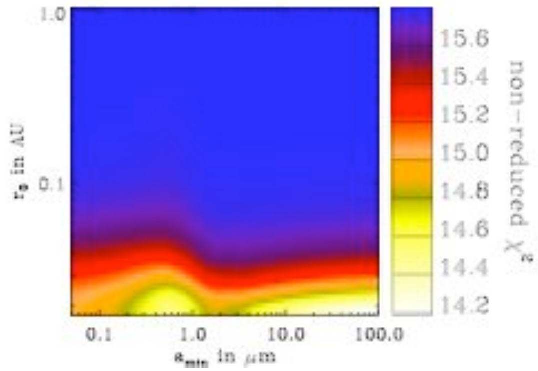
- Excess ~ 10^3 Zodi at 2μm (+6yr RV stability) => safely attributed to dust
- 10/2 μm excess -> grain size, composition, distribution

✓Modeling : **Small grains** are favored (but degeneracy)

✓Density as steep as r^{-4} (solar system: $r^{-0.4}$ with 10-100μm grains)

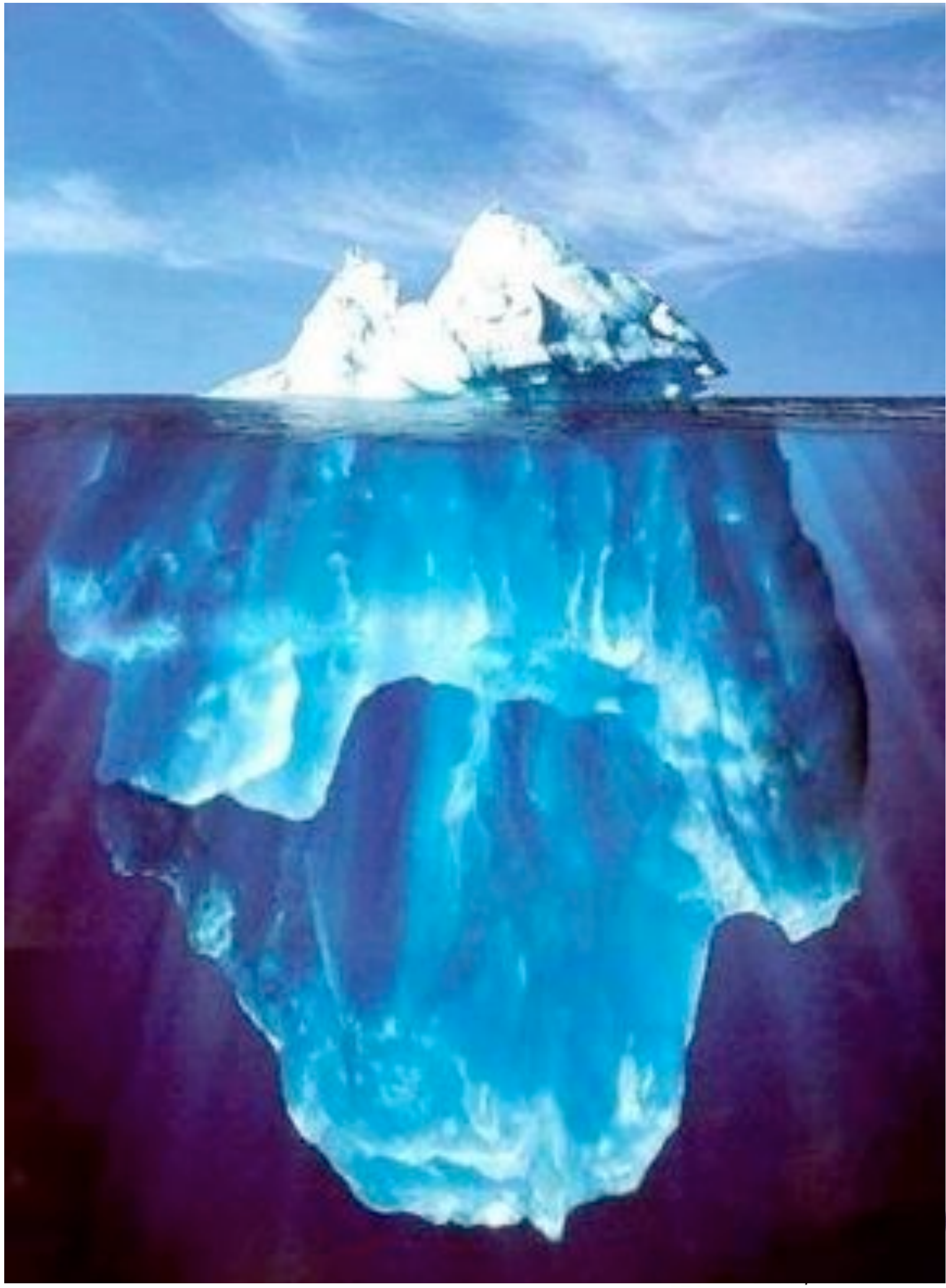
⇒ dust confined in an **annulus (T_{evap}~1500K)**

▪ **Origin** of the hot dust production ? (transient events)



The zodiacal cloud around τ Ceti clearly departs from solar system scheme

Does it represent …



Lessons learned & conclusions

Detections:

$f_{d/*} \sim$ 1-2 % ; $\sigma_f \sim$ 0.2 % ~ few 10^2 zodi
10 x better than 2μm-photometry
visibility accuracy is the key
Not all stars show IR excesses
6-10 measurements for a robust detection
complementary (RV) observations to identify the nature of the excess

A « niche » for interferometry and a « niche » for CHARA/FLUOR (so far)! !

Statistics:

very preliminary rate ~20-30% of reliable detections
search for correlations with SP Type, warm/cold dust, presence of planets ?
On-going program with increased sensitivity
Nov. 2008 campaign very successful (slow seeing !)
(12 more targets, 2-3 detections, reached K=5.8)
planetay systems become accessible (hd69830)
Sample ~ 45 targets with K < 5

Open questions

- Origin of the hot dust production ?
- Frequency =f(amplitude) of 2μm excess
- Time variation of the hot dust excess ?
- Connection hot/warm/cold dust ?
  Link 2-10-24μm excess (if any ?)
- How can we constrain the emission in the habitable zone from our 2μm detections ?
- What impact on the direct detection or characterisation of earth-like planets ?