Unraveling the mystery of hot exozodiacal dust

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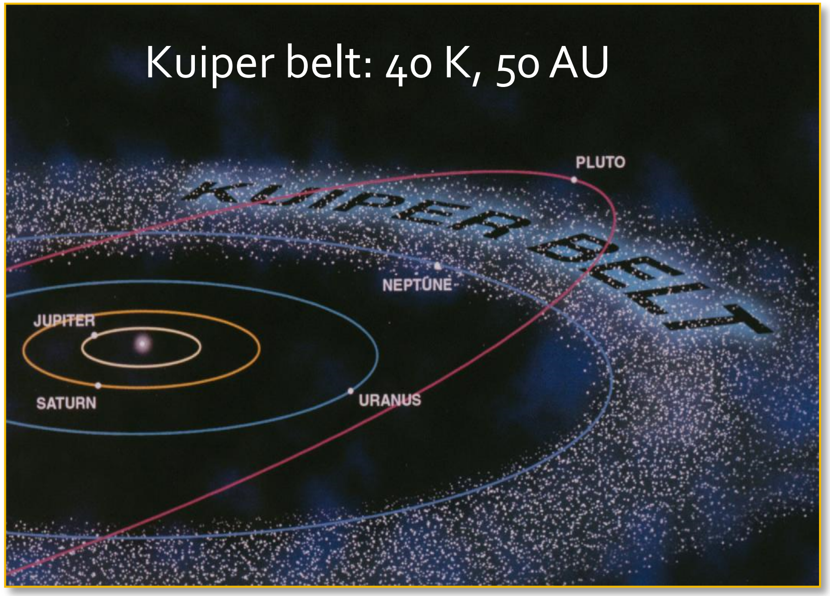
Dust in planetary systems

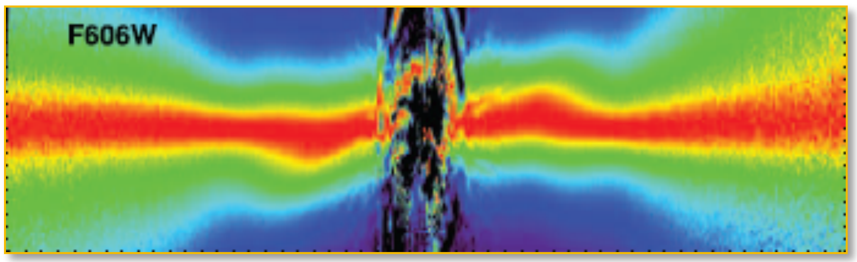
- We all live in a debris disk!
  - 2nd generation dust (asteroids, comets)
- Dust is luminous (**<u>much</u>** more than planets)
- Dust expected in all planetary systems

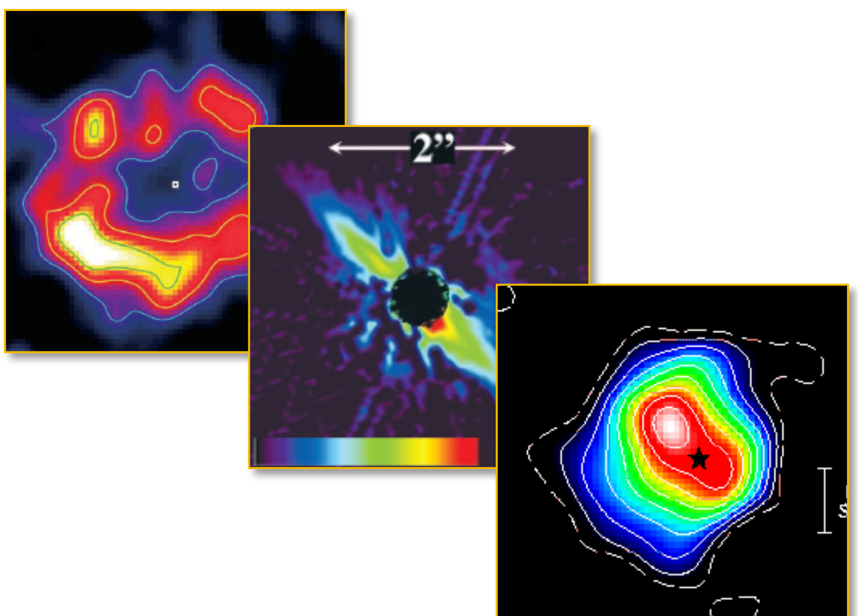


Dust not uniformly distributed

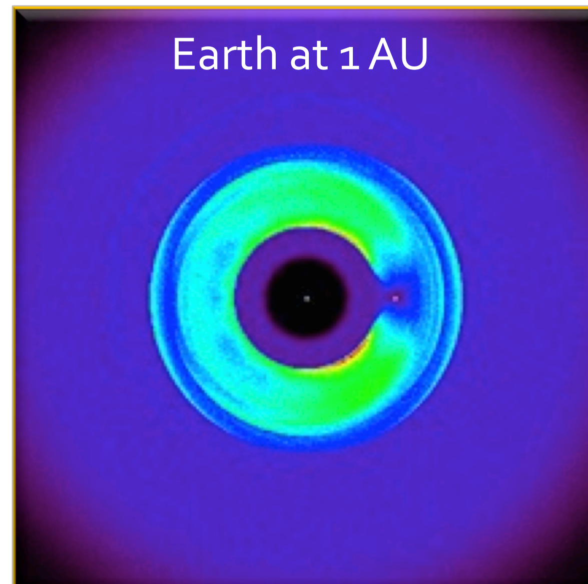
Golimowski et al. 2006; Greaves et al. 2005; Schneider et al. 2005; Holland et al. 1998; Stark & Kuchner 2008; Wyatt et al. 2006

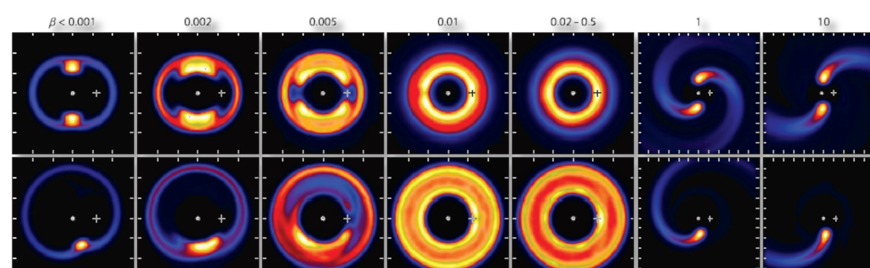
Observations





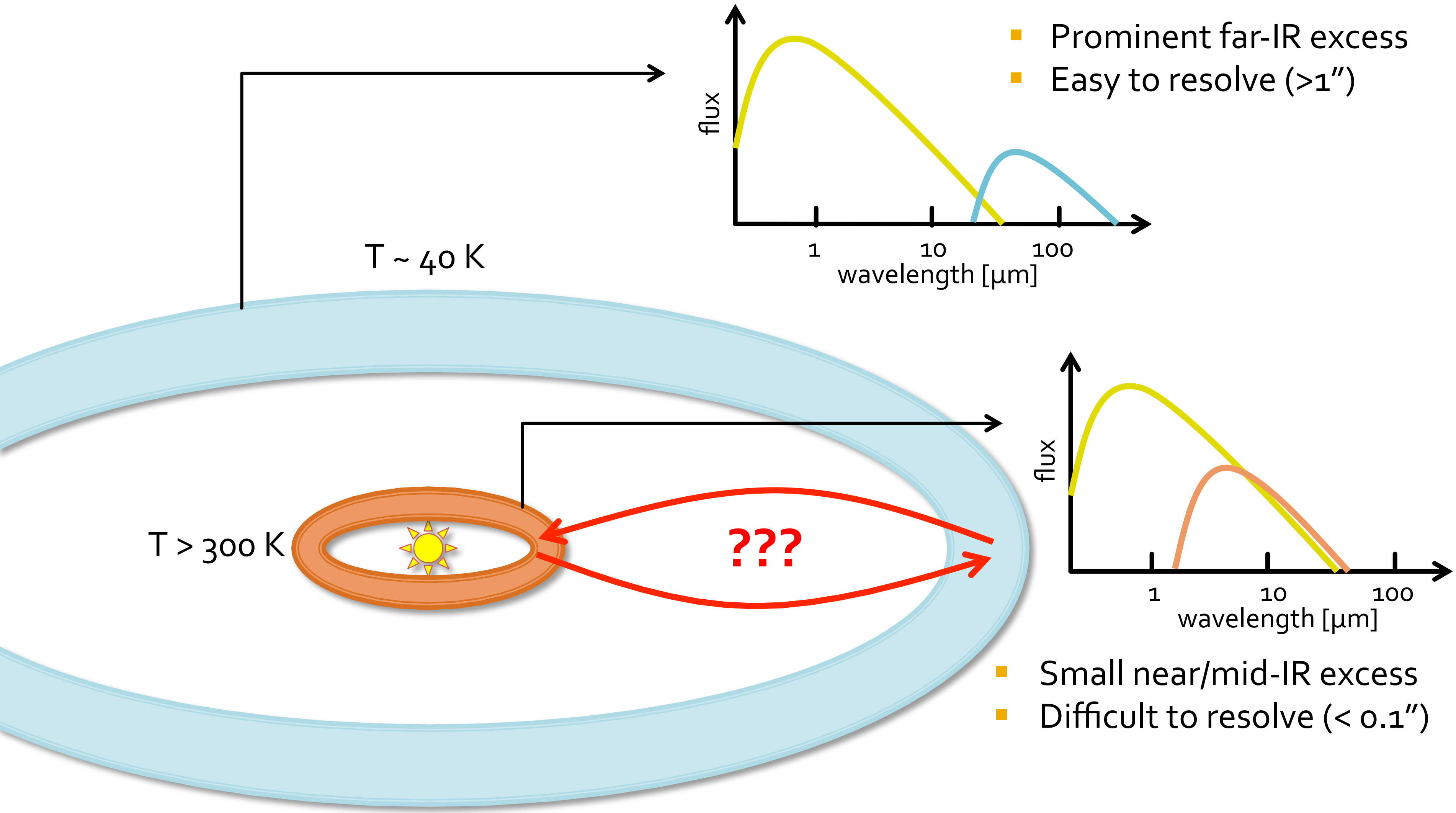
Simulations





Inner vs. outer debris disk

- Prominent far-IR excess
- Easy to resolve (>1″)



- Small near/mid-IR excess
- Difficult to resolve (< 0.1″)

The exozodi problem

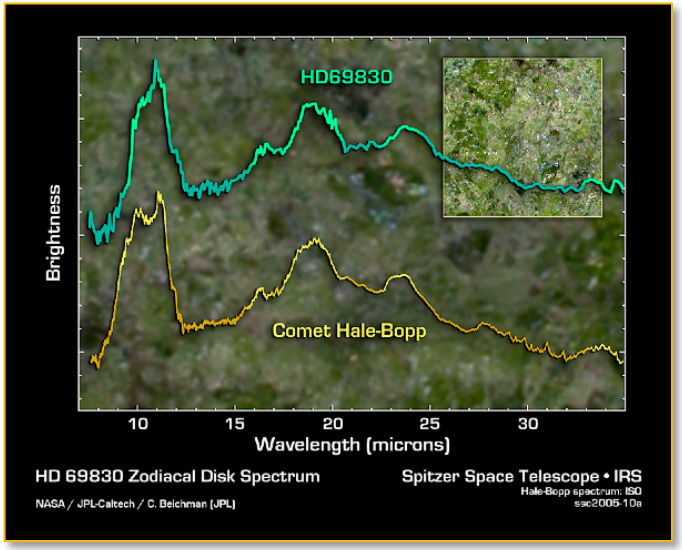
- « A mote of dust suspended in a sunbeam »

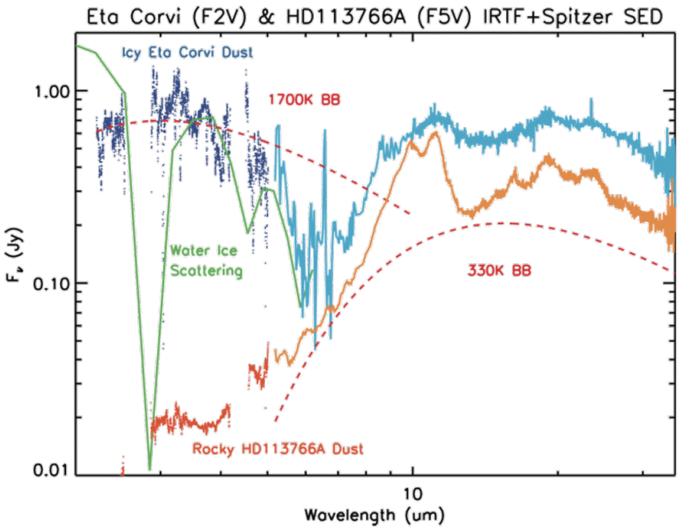
Picture taken by Voyager 1 in 1990 (40 AU from Earth)

Mid-infrared spectro-photometry

Beichman et al. 2006; Lisse et al. 2012

- Sensitivity ~1000 zodi
  - Spitzer/IRS (5-34 μm)
  - Spitzer/MIPS (24 μm)
  - WISE (12μm, 22μm)
- Statistics
  - ~1% warm excess
- Limited by
  - Photometric accuracy
  - Model of the stellar photosphere



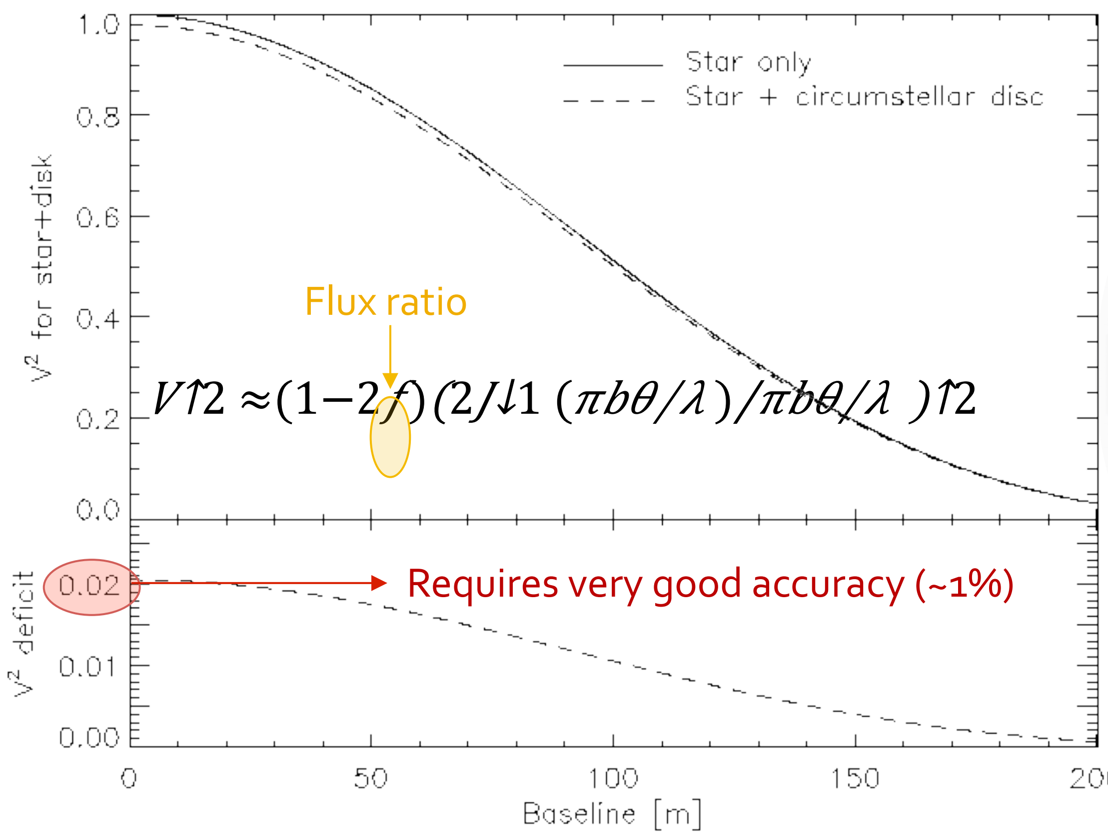


Near-IR interferometry

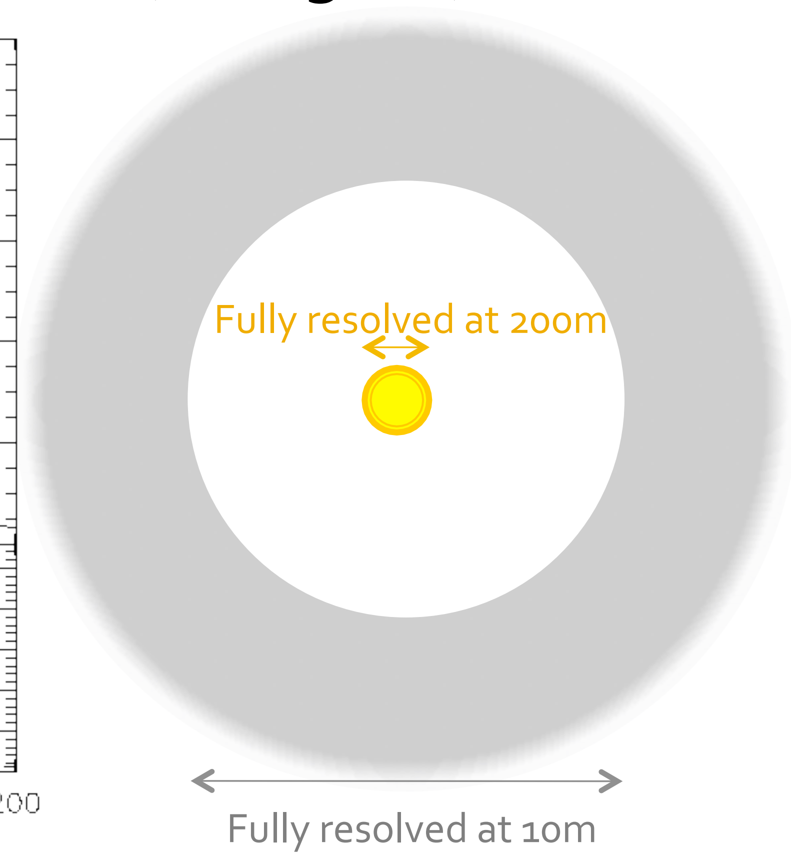
Principle and first results

Principle of exozodi detection

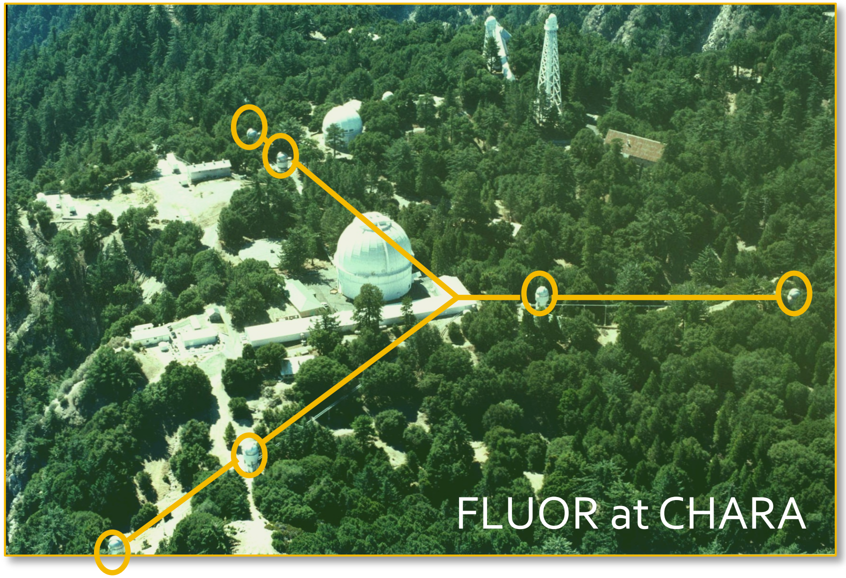
- Disk larger than λ/B → visibility loss
- Best detected at short baselines (~10-30m)



$$V^2 \approx (1-2f)\left(\frac{2 J_1(\pi b\theta/\lambda)}{\pi b\theta/\lambda}\right)^2$$

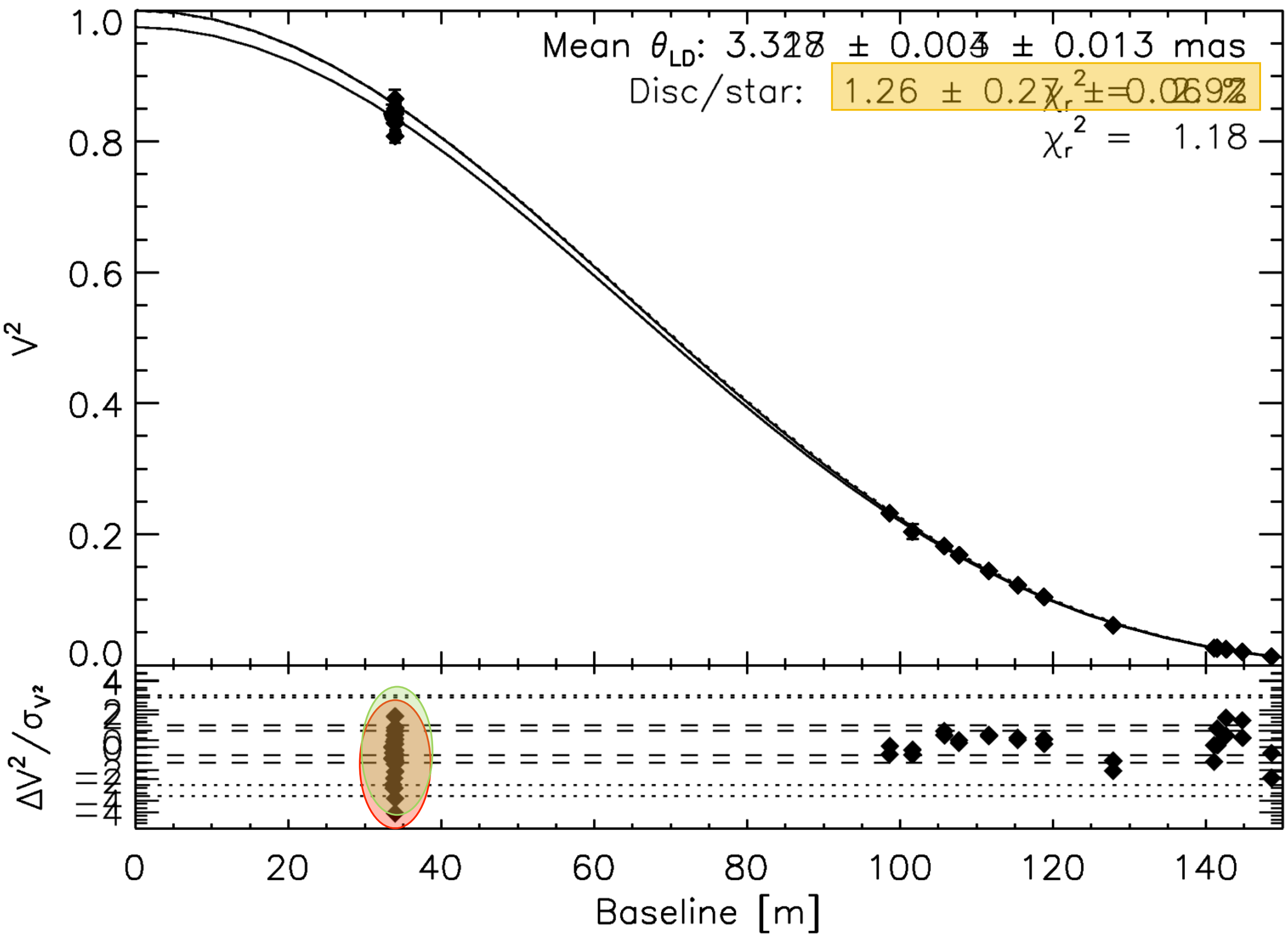


High precision interferometers



Vega viewed by CHARA/FLUOR

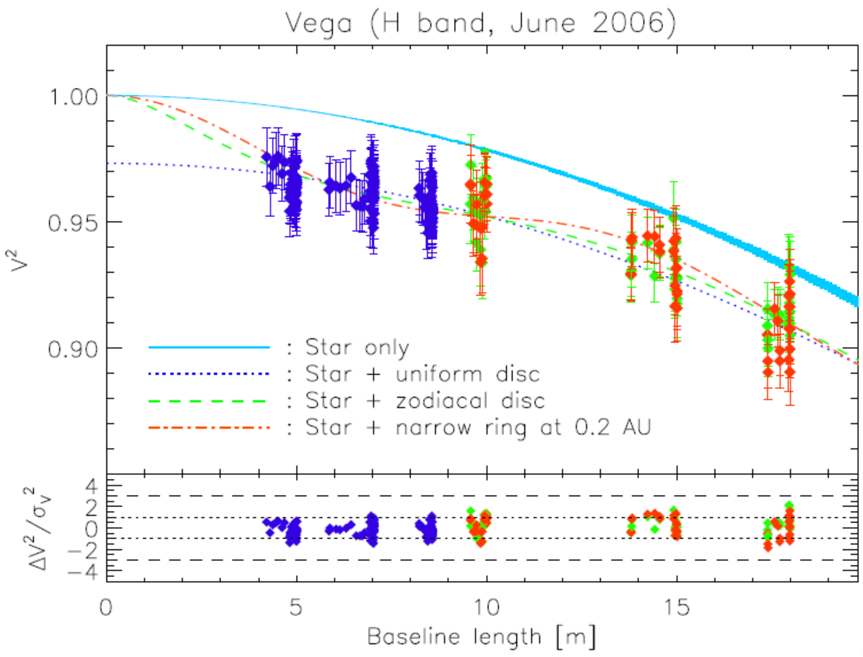
Absil et al. 2006

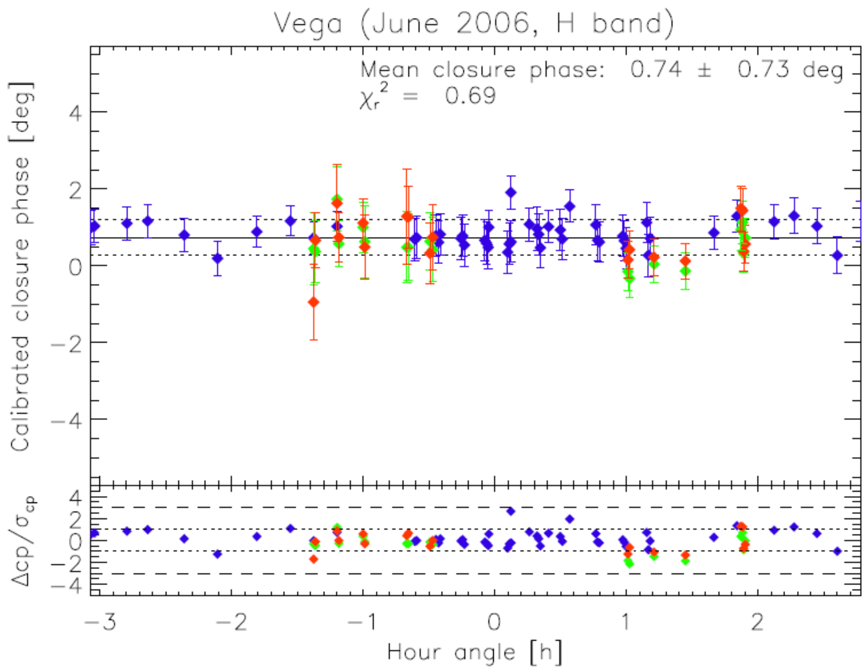


Morphology?

Defrère et al. 2011

- H-band short baseline data (IOTA/IONIC)
  - No closure phase → not a point-like source
  - Dust distribution not constrained





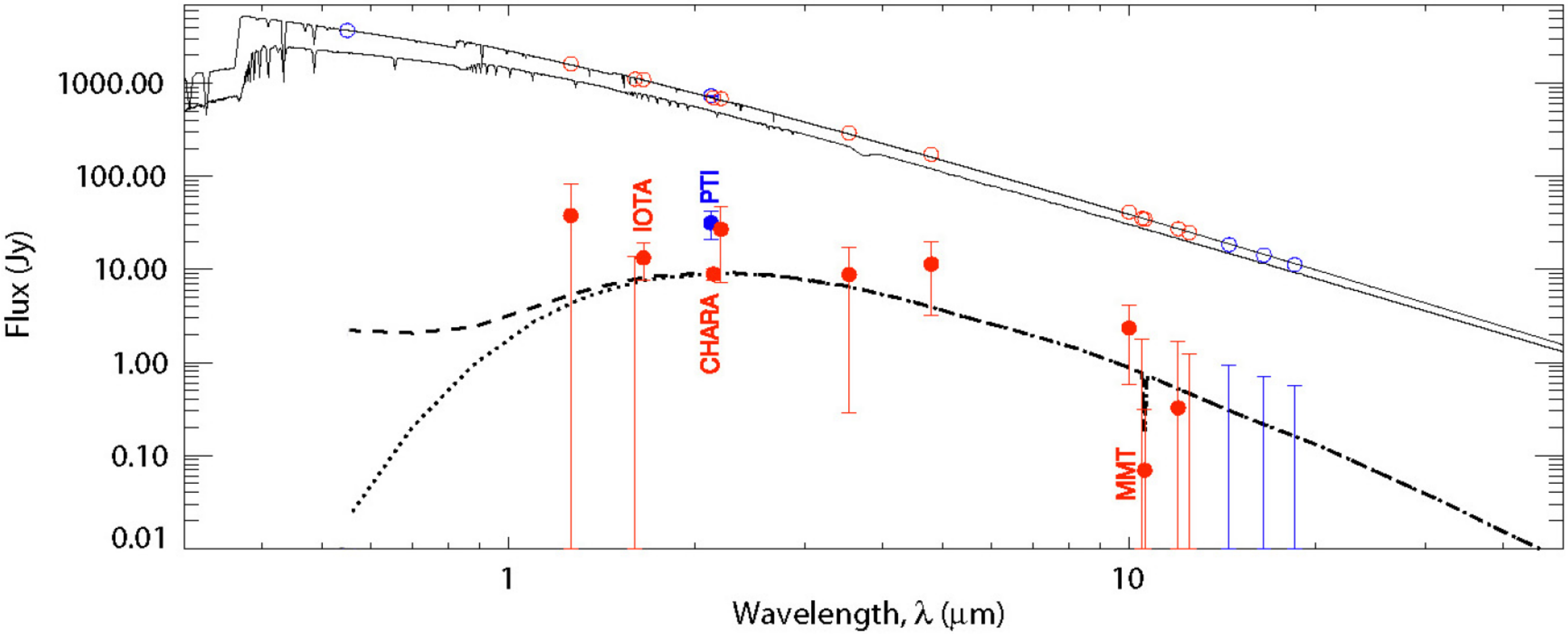
Sources of near-IR excess?

- Point-like source?
  - No closure phase signal
  - RV and astrometry stable
  - Very low probability for background star
- Stellar wind / circumstellar gas?
  - A stars: very weak winds (~$10^{-12..14}$ $M_{\odot}$/yr)
  - Free-free emission: should be stronger at mid-IR
  - Ae/Be phenomenon: no evidence for Hα emission
- Circumstellar dust?
  - Thermal emission & reflected flux
- New, unknown phenomenon?

Radiative transfer modeling

Defrère et al. 2011

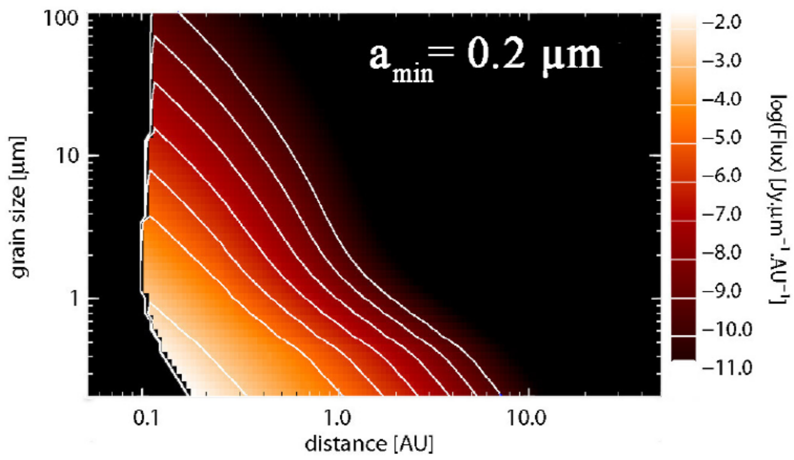
- H- and K-band interferometry
- N-band nulling interferometry (MMT/BLINC)
- Archival near- to mid-IR spectro-photometry

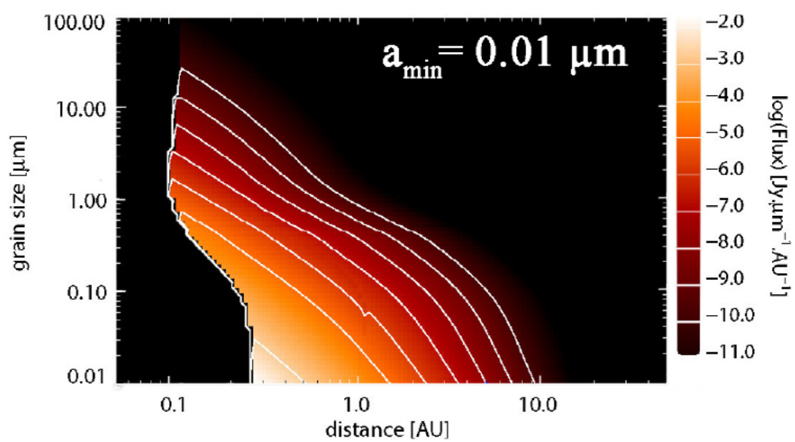


Most probable dust properties

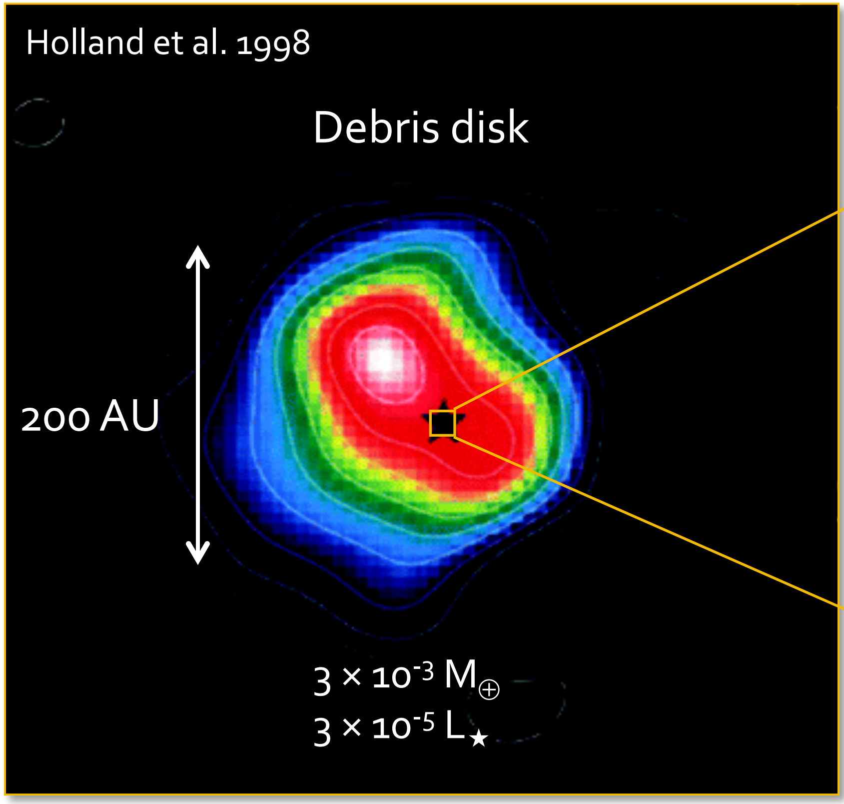
Defrère et al. 2011

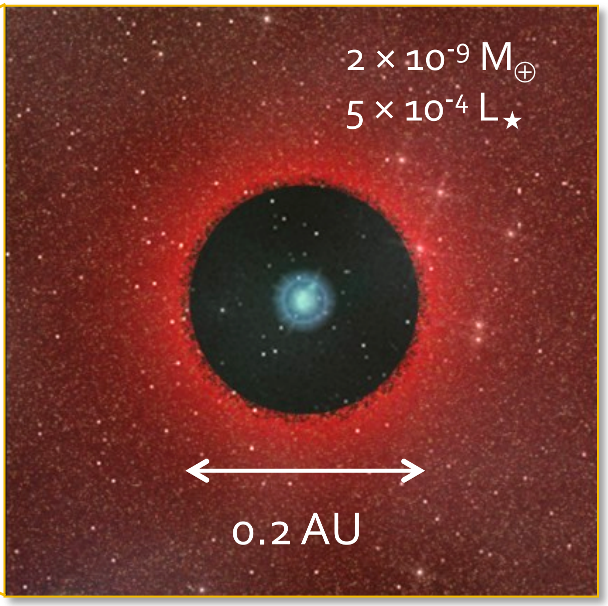
- Bayesian χ^2 analysis of large parameter space
  - Grains < blowout size
  - Hot grains (> 1000 K)
  - Presence of carbons ≥ 10%
  - Distance: ~ 0.1 – 0.5 AU
  - Steep density power law: $\alpha < -3 \rightarrow$ ring?
- Mass: $\sim 2\times10^{-9}\ M_{Earth}$
- Luminosity: $\sim 5\times10^{-4}\ L_{star}$





New view of Vega





The EXOZODI project

- 4-year ANR project (2010-2014)
  - PI: J.C. Augereau (IPAG, Grenoble)
  - Goal: understand the origin of bright exozodis
- 5 work packages
  - Instrumentation
  - Observations & data analysis
  - Radiative transfer modeling
  - Simulations (dynamics & collisions)
  - Development of new simulation tools

A near-IR survey

CHARA/FLUOR observations

Survey at CHARA/FLUOR

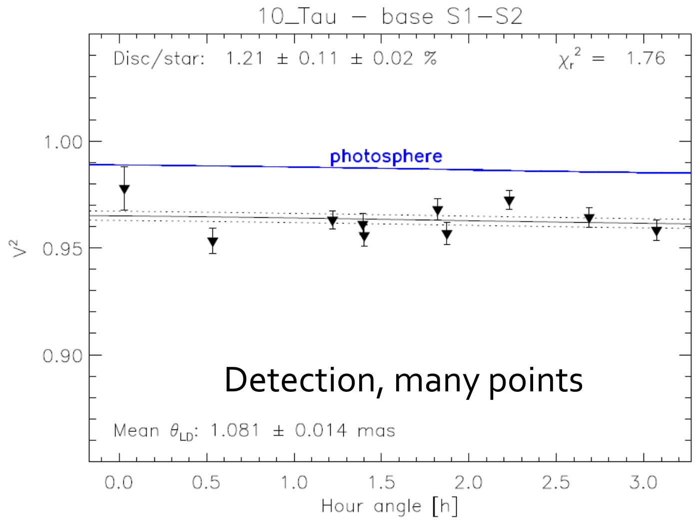
Absil et al. 2013

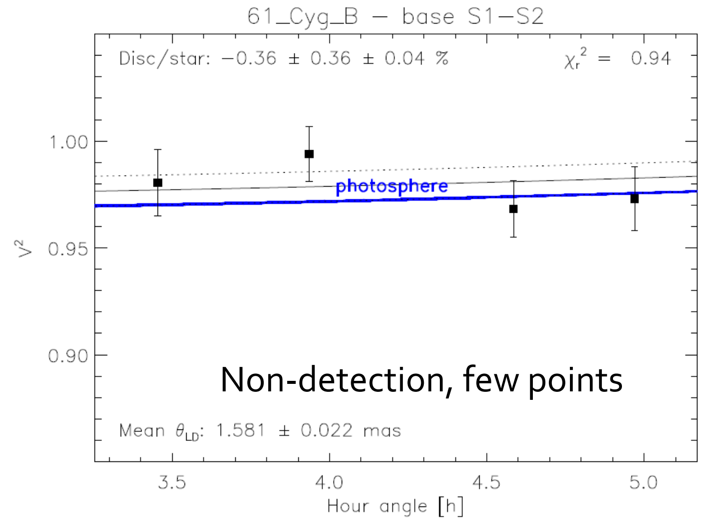
- Magnitude-limited sample
  - (All) northern stars with far-IR excess and K<4
  - ~ same amount of "non-dusty" stars
- Evenly spread between spectral types A, F and G-K
- Diameters predicted from surface-brightness relationships

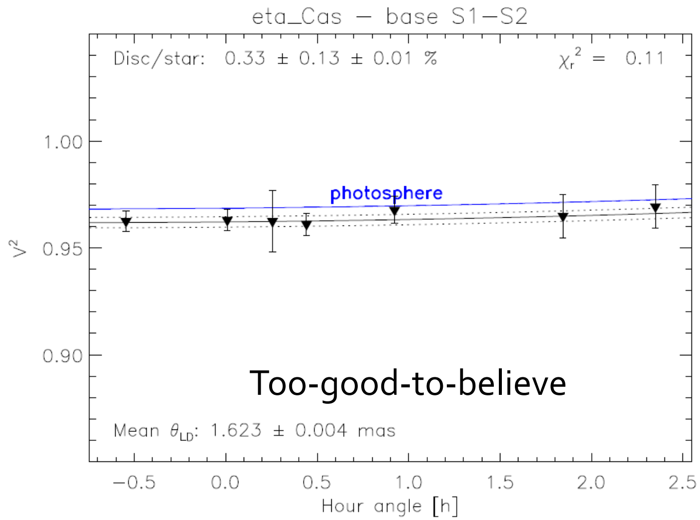
	Dusty	Clean	Total	<Kmag>
A	7	5	12	2.4
F	7	8	15	2.7
GK	5	10	15	2.7
Total	**19**	**23**	**42**	**2.6**

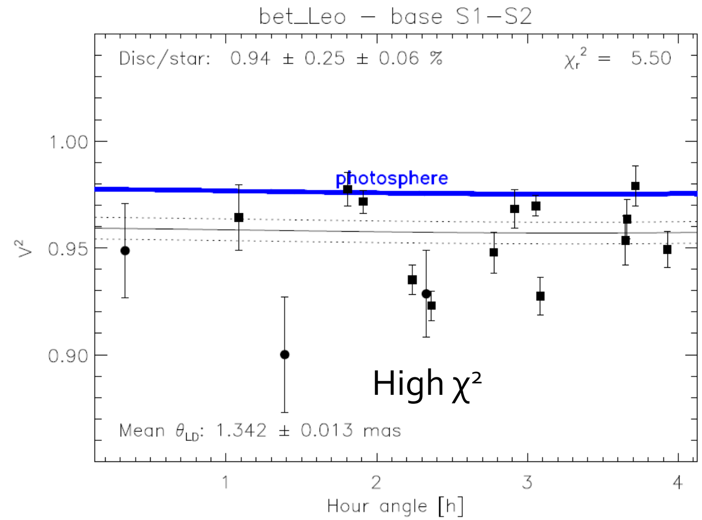
Examples (V^2 vs hour angle)

Absil et al. 2013





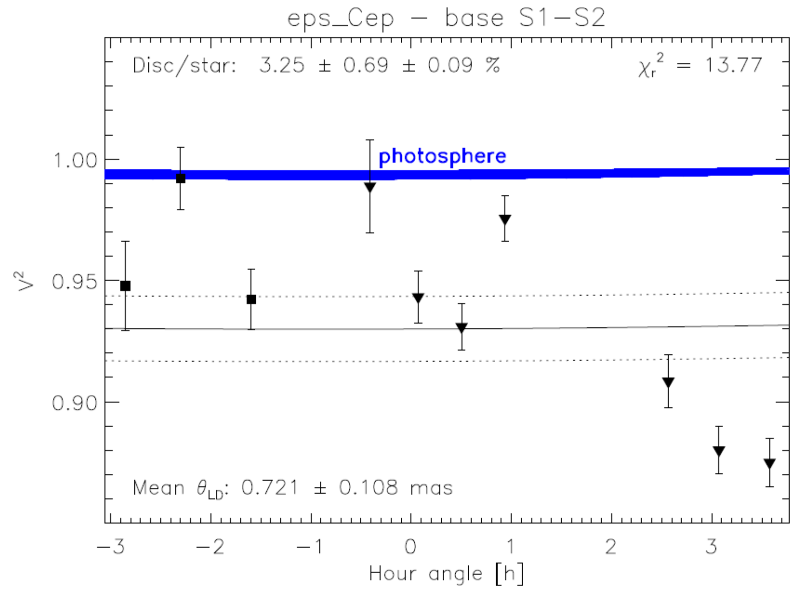


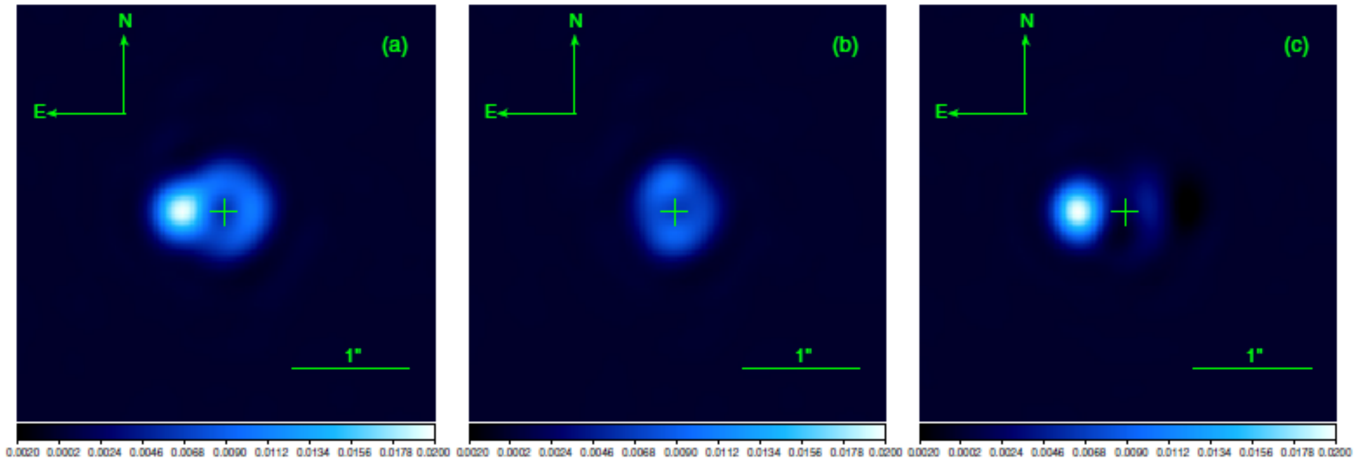


eps Cep: a faint close companion

Mawet et al. 2011; Absil et al. 2013

- Wavy pattern in visibilities (→ large χ^2)
- Confirmed with coronagraphy
  - 330 mas separation
  - 2% flux ratio

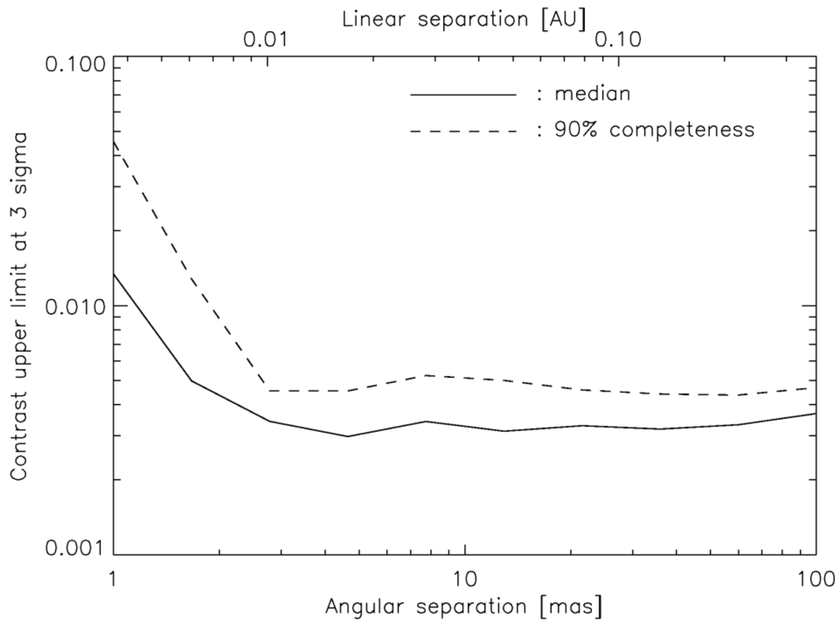




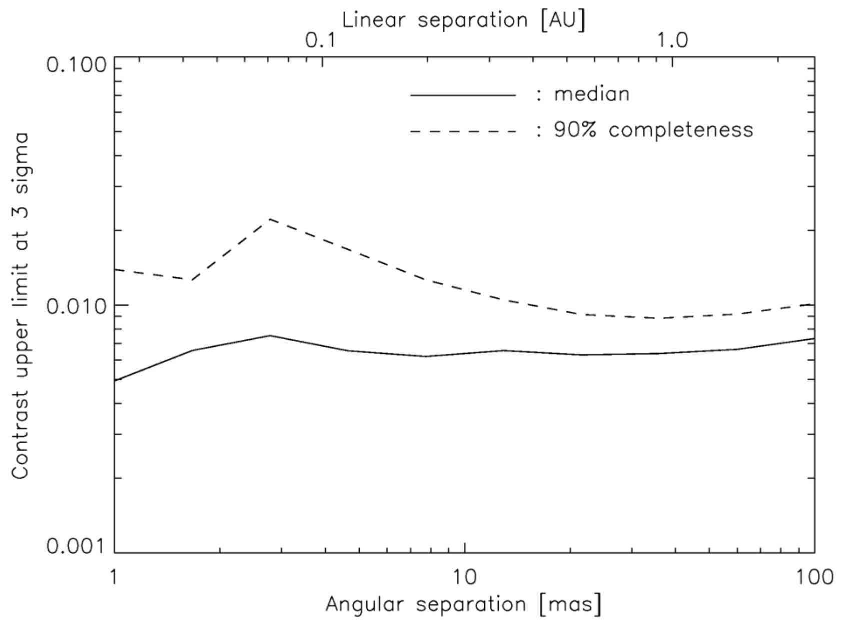
More follow-up examples

Absil et al. 2013

tau Cet
(VLTI/PIONIER data)



zet Aql
(CHARA/MIRC data)

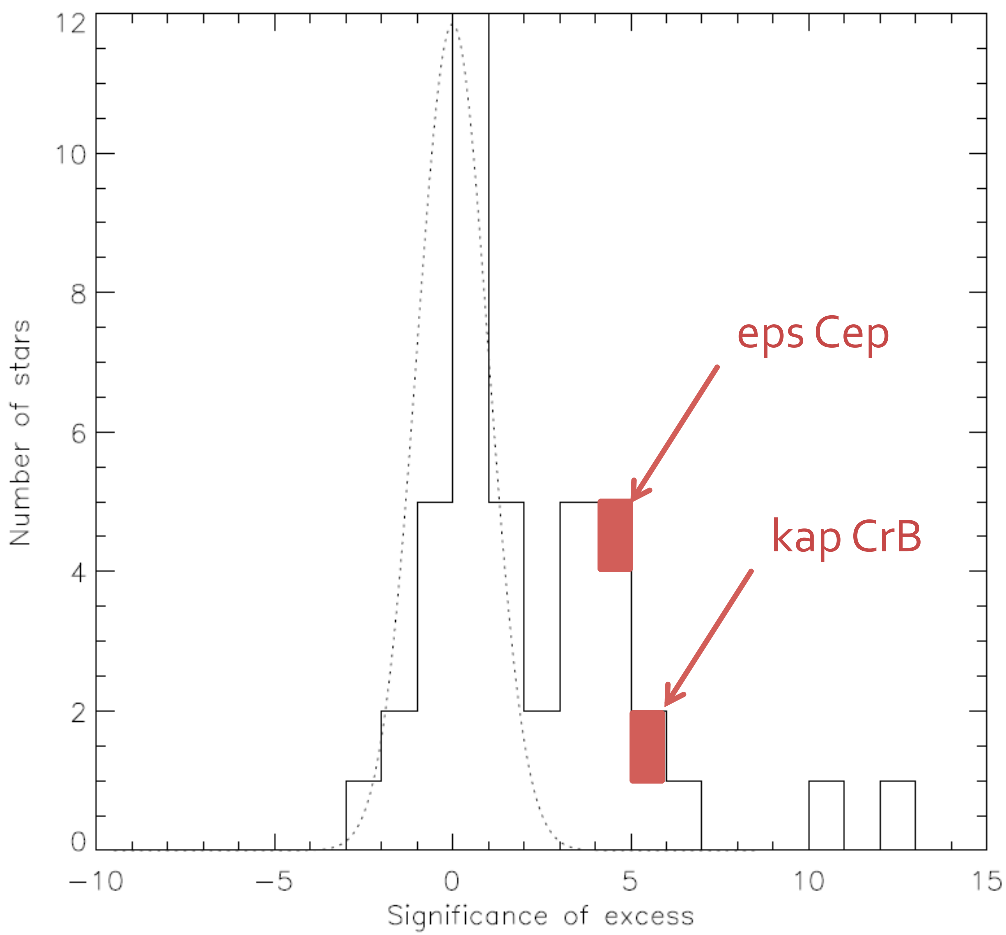


Caveat: not all excesses followed up!

Survey summary (42 stars)

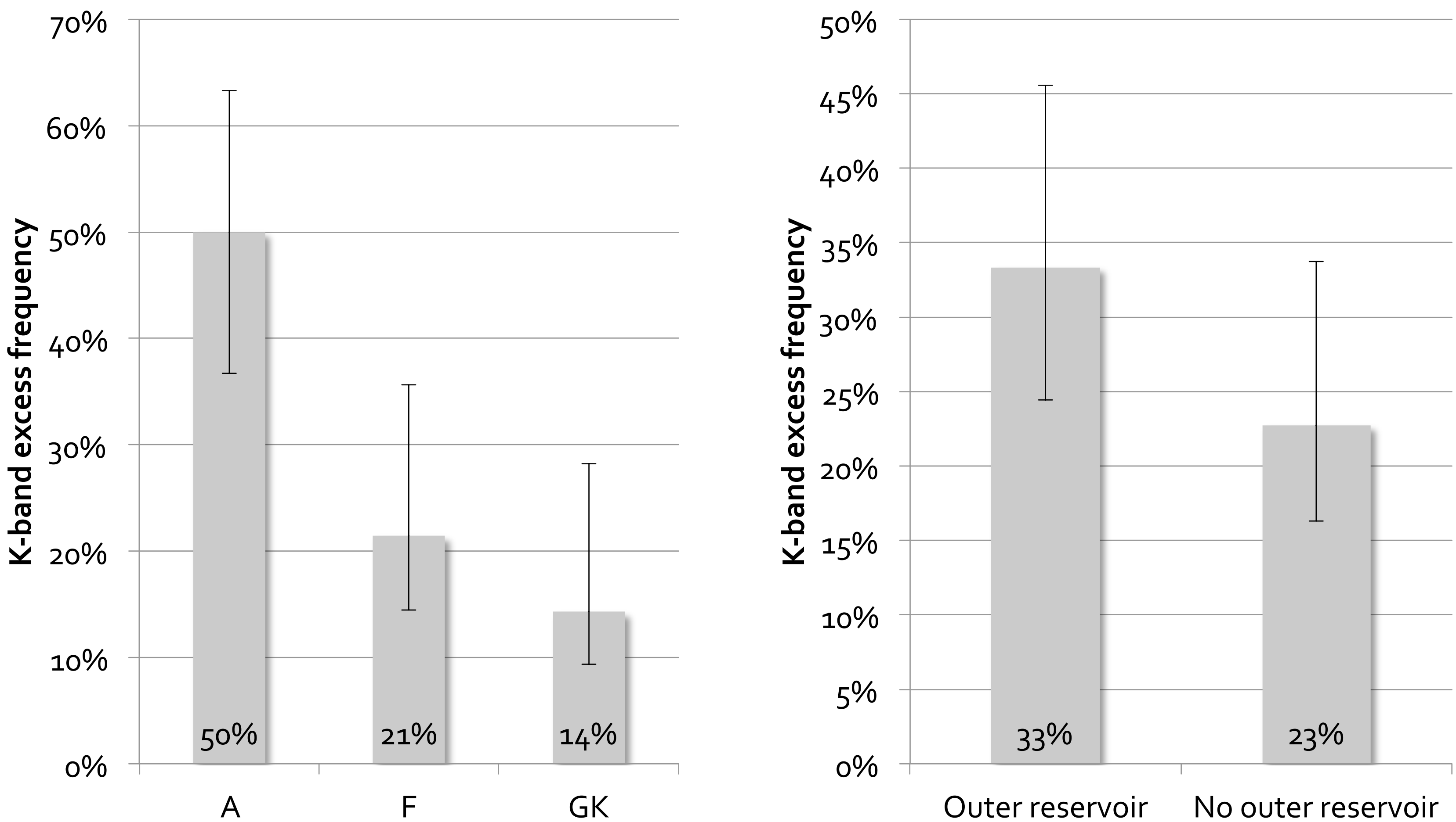
Absil et al. 2013

- Mean sensitivity: 0.27% at 1σ
- $0.3 < \chi_r^2 < 3$ for most targets
- Core distribution looks Gaussian
  - No target with significance < -3σ
  - Slight offset (0.5σ)
- Threshold at 3.5σ
  - 11 excesses out of 40 stars → 28^{+8}_{-6} %



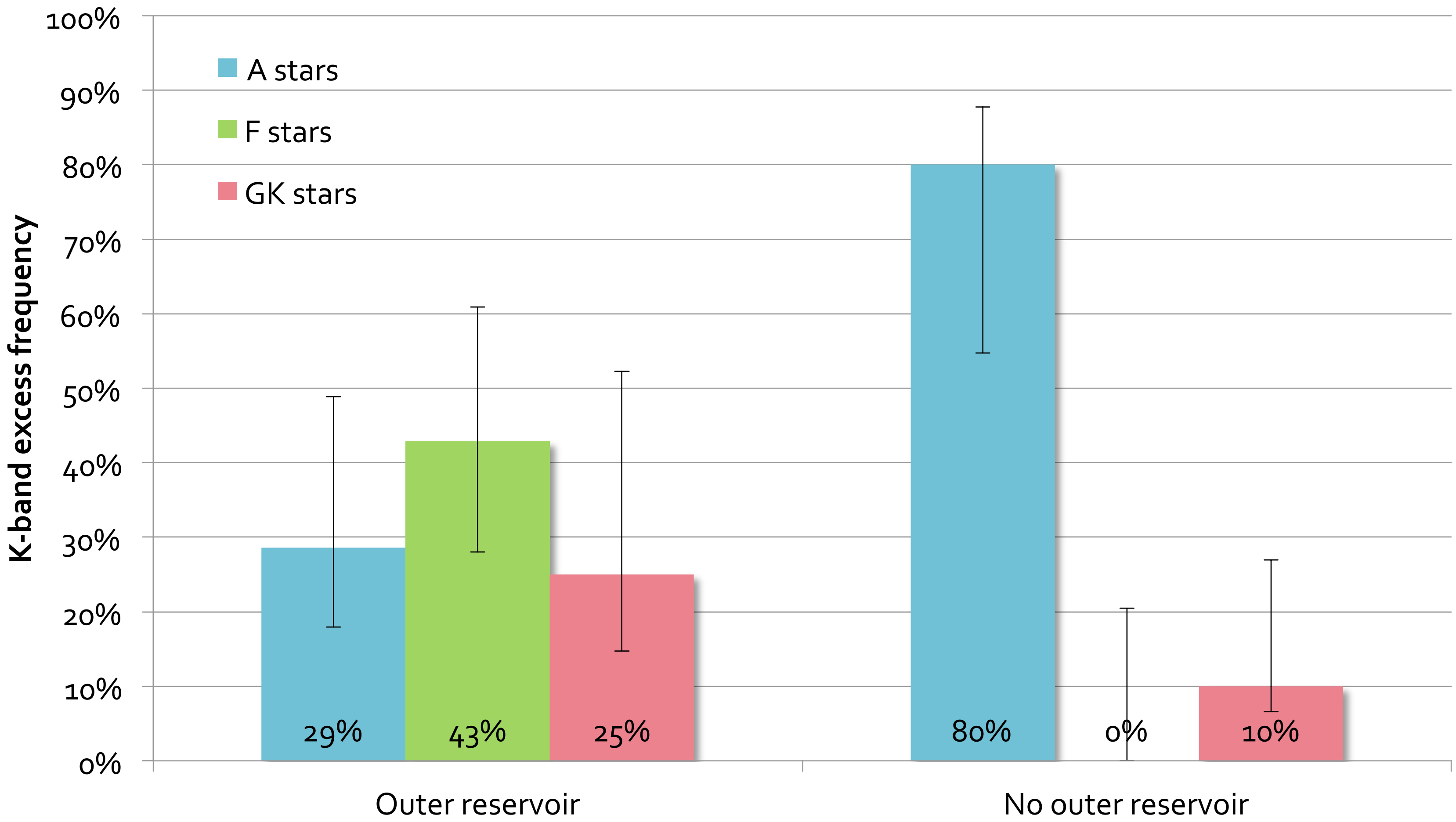
Statistical trends

Absil et al. 2013



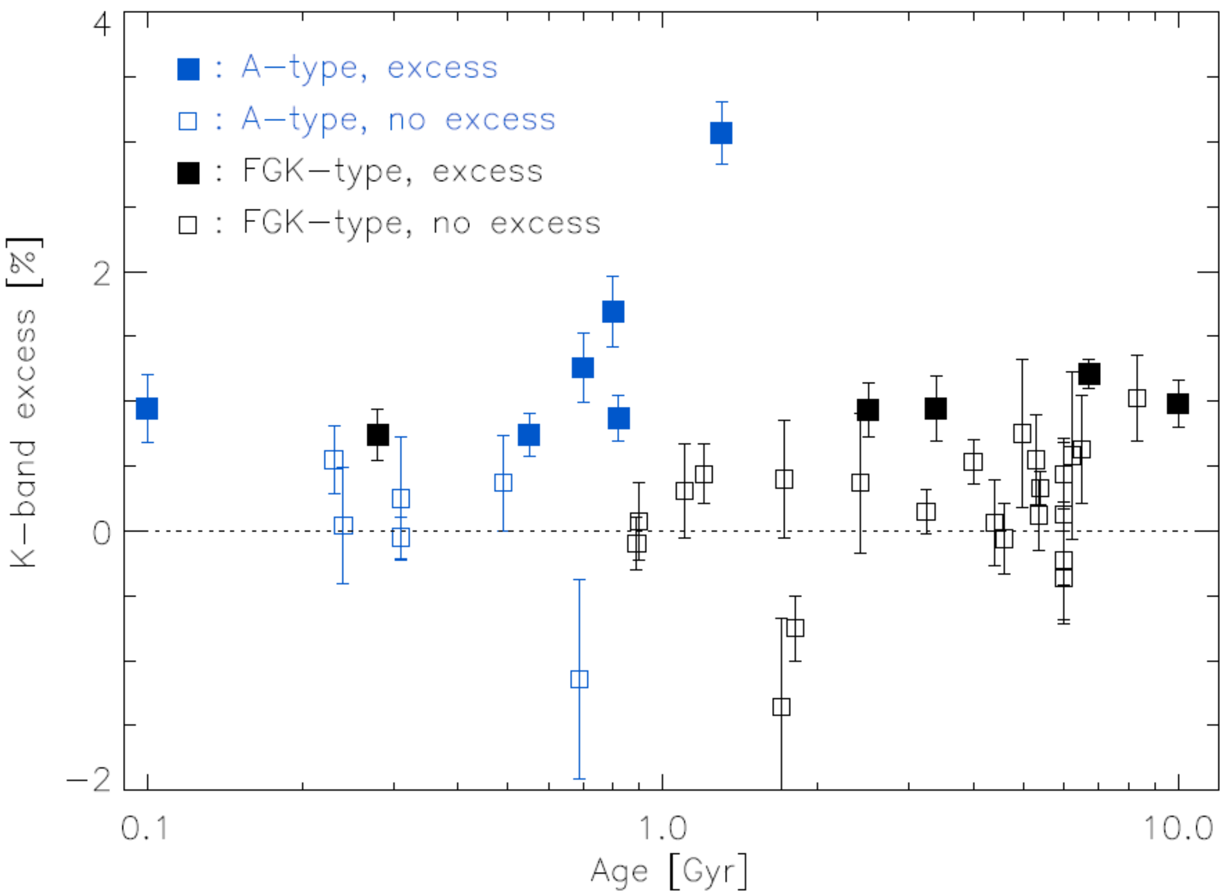
Correlation type/cold dust/hot dust

Absil et al. 2013



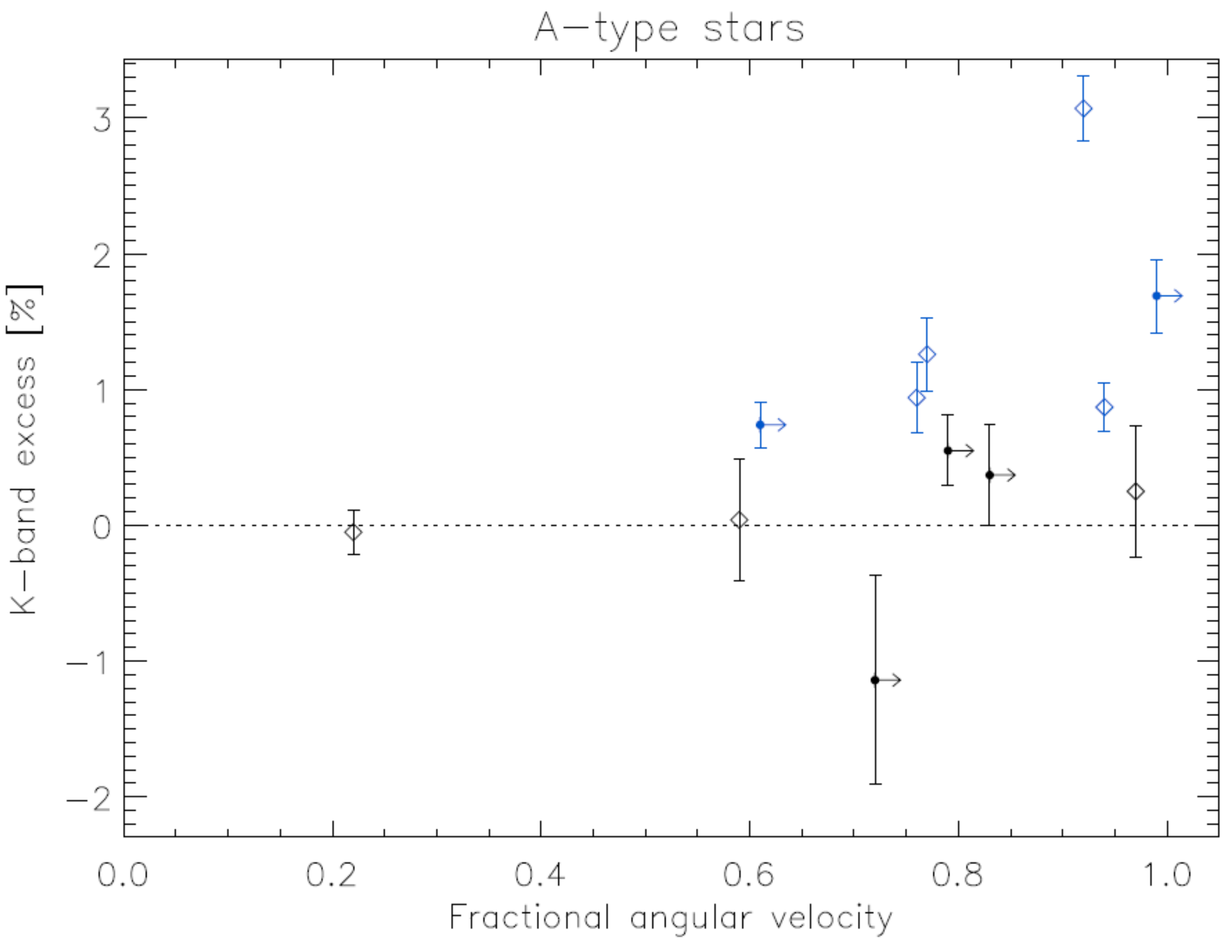
Correlation vs age?

Absil et al. 2013



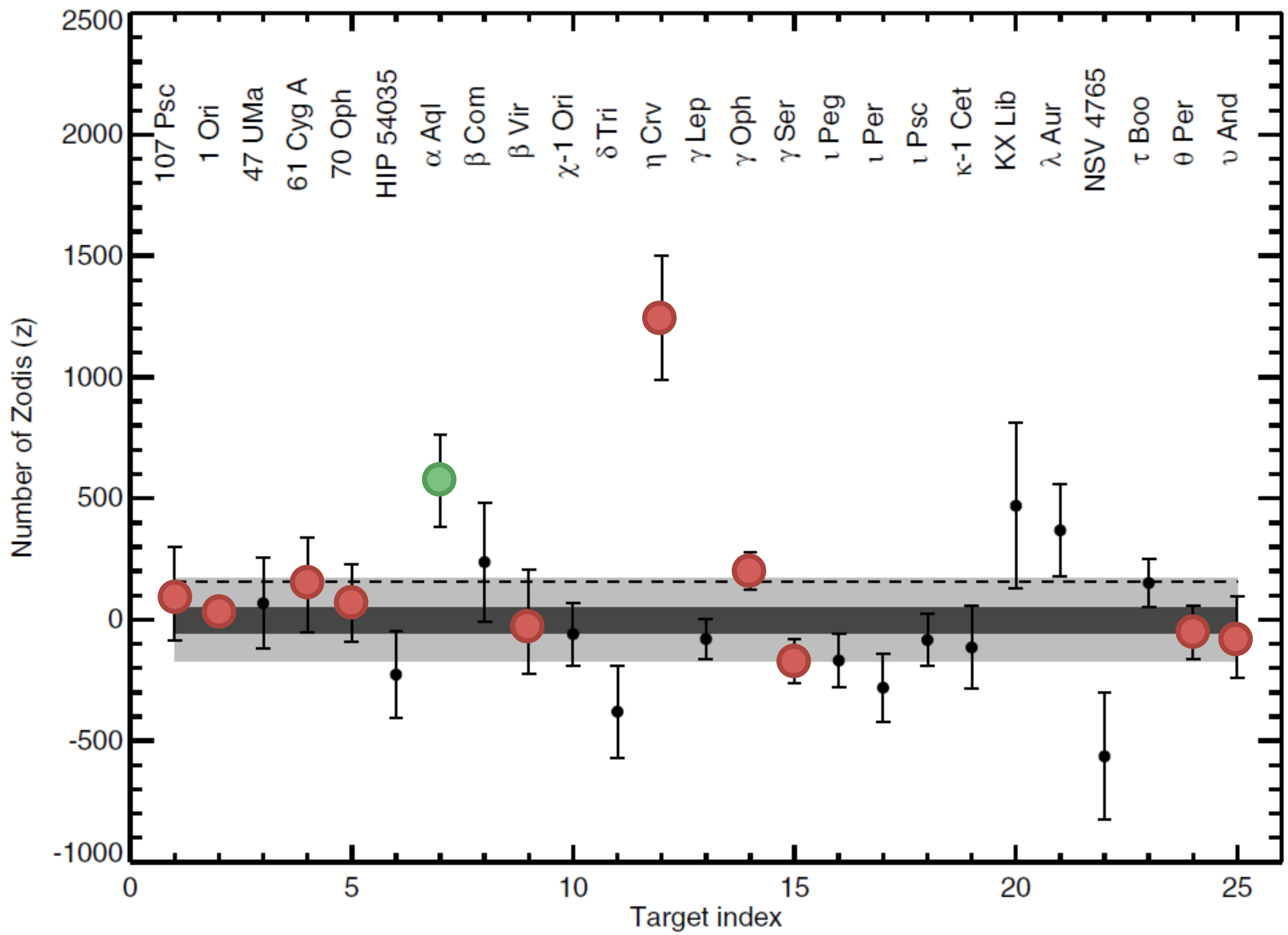
Correlation vs rotational velocity?

Absil et al. 2013



Comparison with KIN

Millan-Gabet et al. 2011



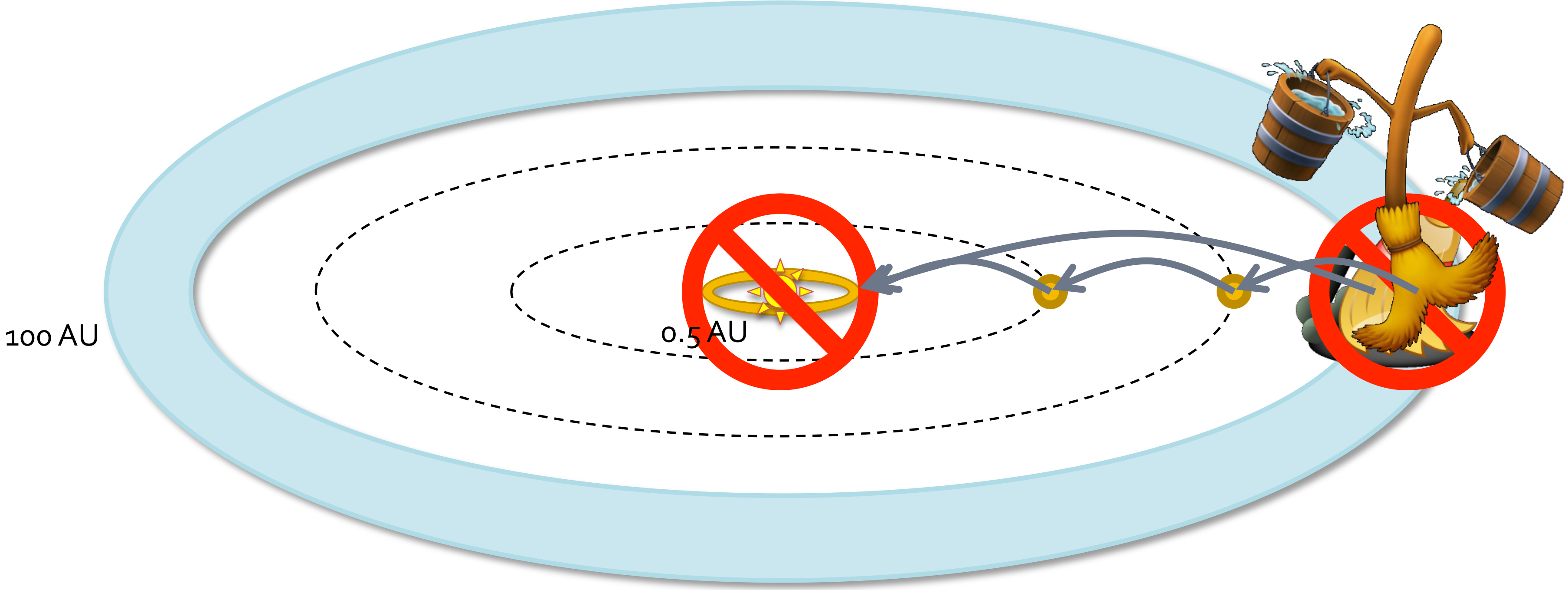
More KIN follow-up to come…

Origin of the dust?

Some results of the EXOZODI project

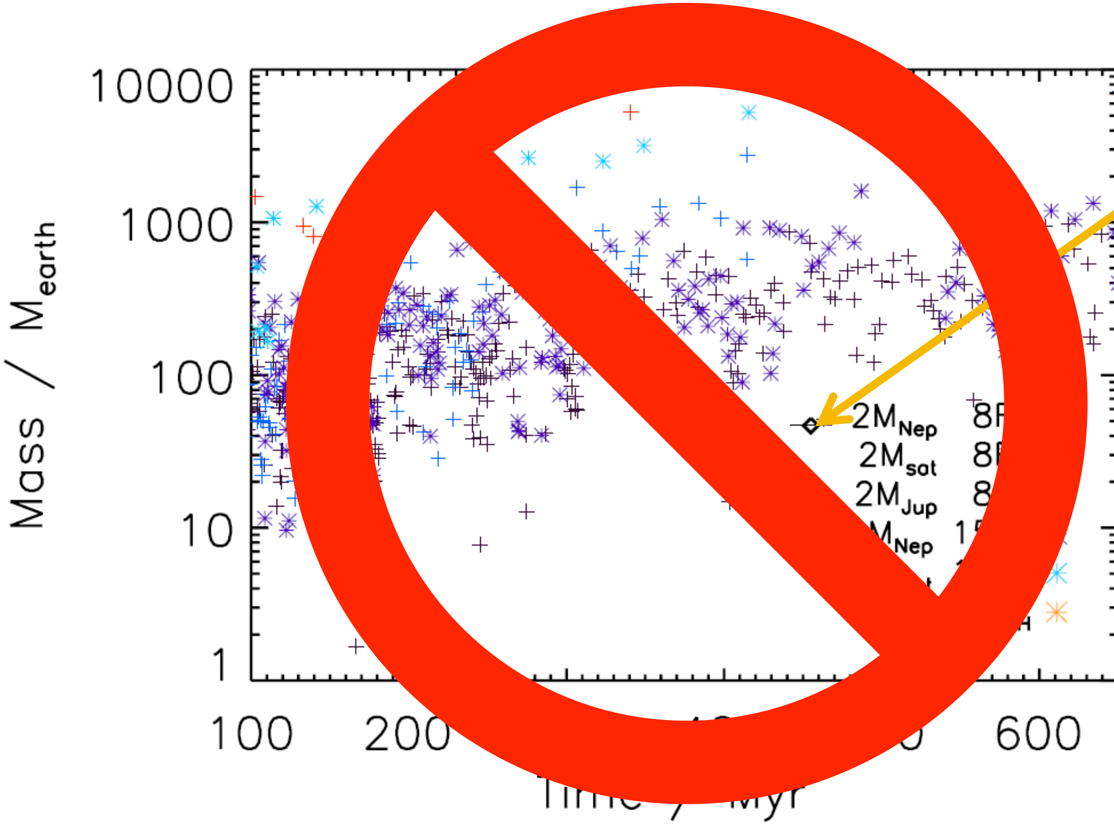
Steady state?

- Local production?
- Connection to outer disk?
  - Poynting-Robertson drag?
  - Multiple scattering of comets?



N-body simulations for Vega

Bonsor et al. 2012

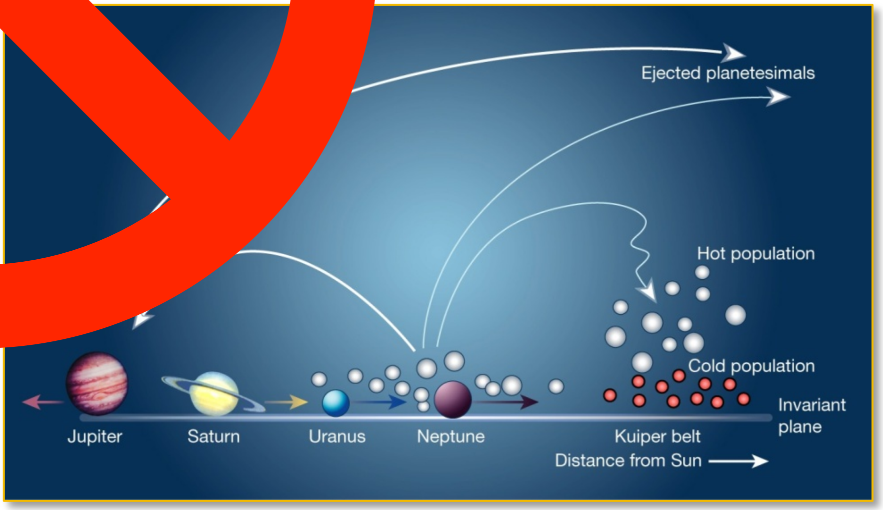


Vega:
700/455 Myr,
46.7 M_{Earth}
(Monnier12)

Fig. 12. Total outer belt mass required if scattering by a chain of equal mass planets, as shown in Fig. 9, or detailed in Table 3, is to replenish an exozodi inside of 1 AU around Vega at the required rate of $10^{-9}\ M_{\oplus}/\mathrm{yr}$.

Origin of hot dust: transient?

- Isolated event?
  - Large collision (e.g. Earth-Moon)
  - Break-up of gi ... et
- Dynamical perturbation
  - Falling Evap ... ting Bodies
  - Late Heavy Bombardment
- **Low probability**

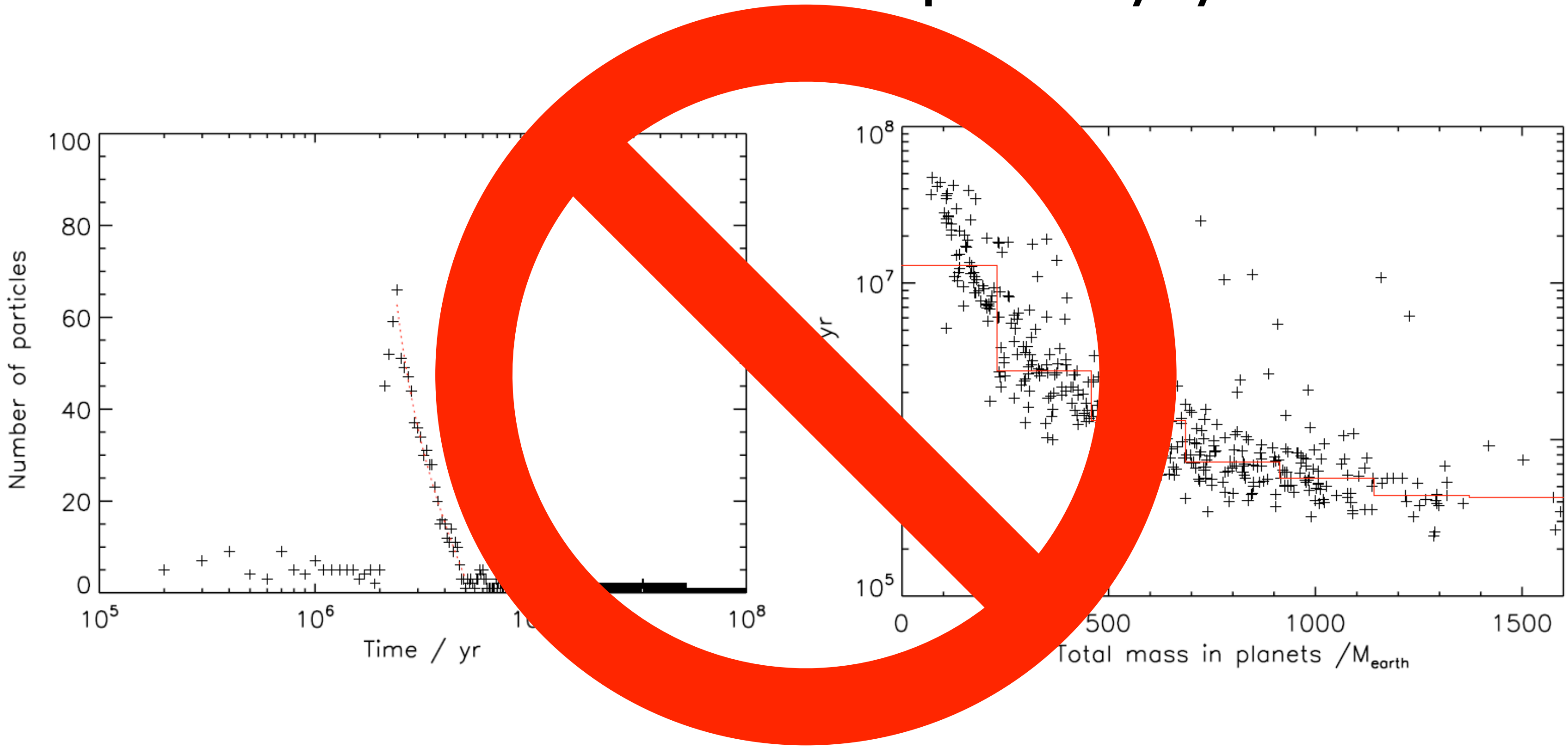


Long lived LHB aftermath?

Bonsor et al. 2013

 # test particles within 5 AU

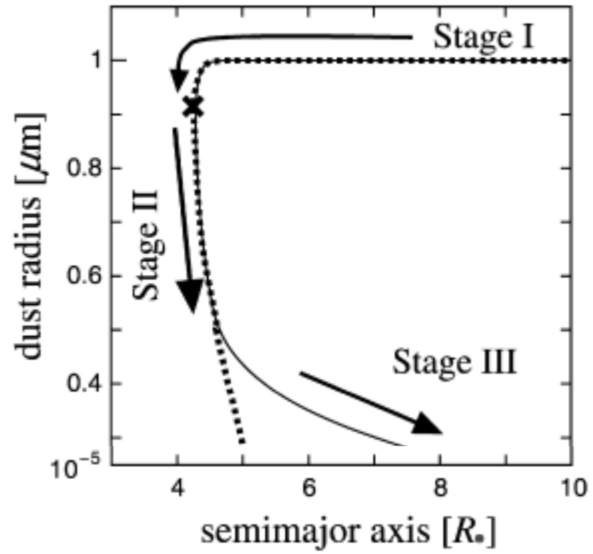
Aftermath timescale vs. planetary system mass

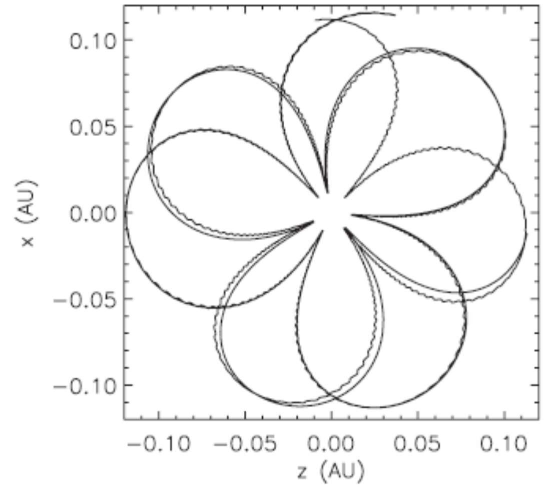


Dust trapping mechanisms?

Kobayashi et al. 2009; Czechowski & Mann 2010; Su et al. 2013; Lebreton et al. 2013

- Accumulation of dust at sublimation radius
  - PR drag vs sublimation
- Magnetic trapping
  - Applicable to nano dust
  - At work in Solar system
- Gas trapping
  - Gas resulting from grain sublimation?





Extending the survey

First results with VLTI/PIONIER

Enlarging the statistical sample

- New targets: Spitzer, Herschel cold disks
- Go fainter
  - Refurbished FLUOR → "JOUFLU"
  - New camera, upgraded optics
  - Expect high-precision down to K~5
- Go South
  - PIONIER at VLTI
  - High-precision V^2 down to H~5
  - Same fringe scanning principle as FLUOR
  - 6 (short) baselines at a time → huge gain in speed

PIONIER survey status

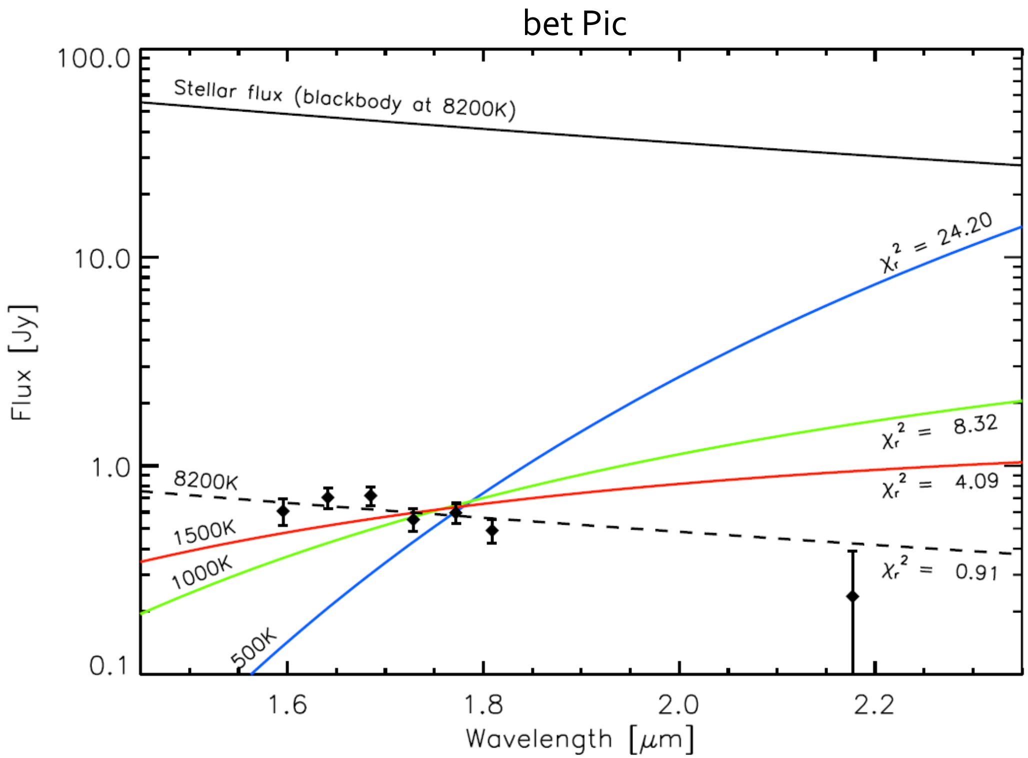
Ertel et al., in prep

- 4 × 3n awarded in 2012
  - 89 stars observed
- Data reduction still on-going
  - PIONIER stability validated
  - VLTI polarization effect identified
  - V^2 accuracy on spec after correction
- Overall detection rate consistent with FLUOR
- Follow-up activities (color, variability, etc)
  - Dec. 2013: new detector → go even deeper

New feature: low-res spectra

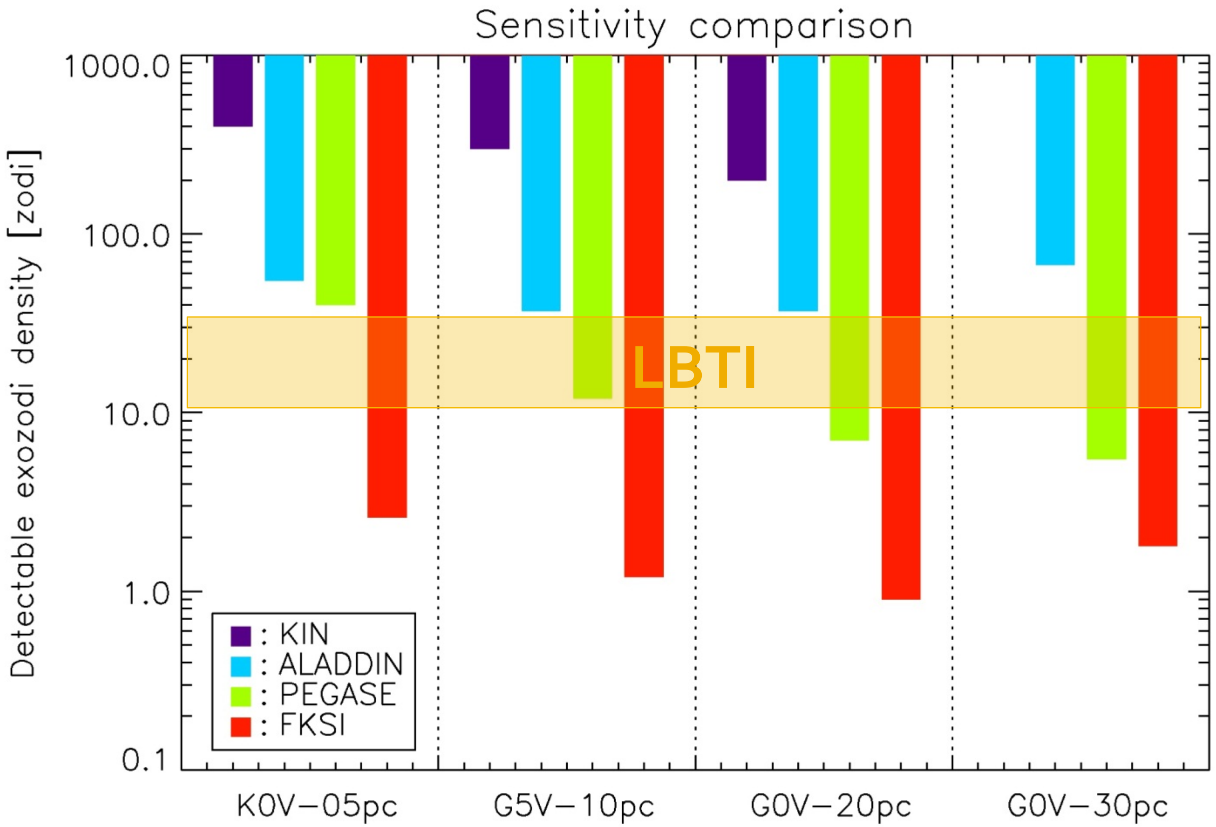
Defrère et al. 2012

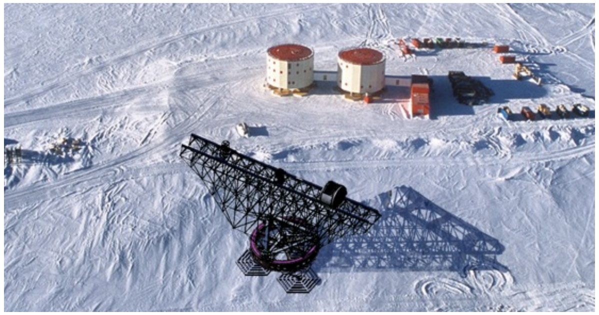
- Dispersed fringes with PIONIER (soon FLUOR)
  - Flux ratio measurements across H and/or K band
  - Direct constraint on dust temperature

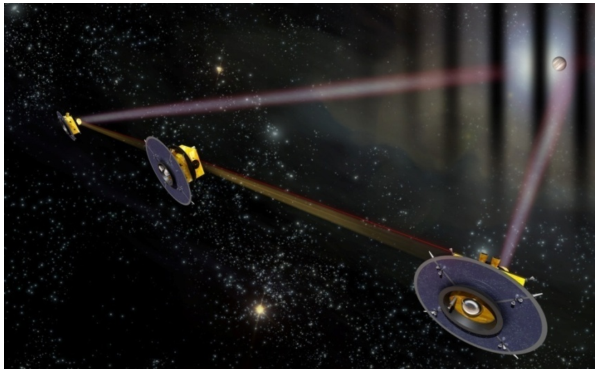


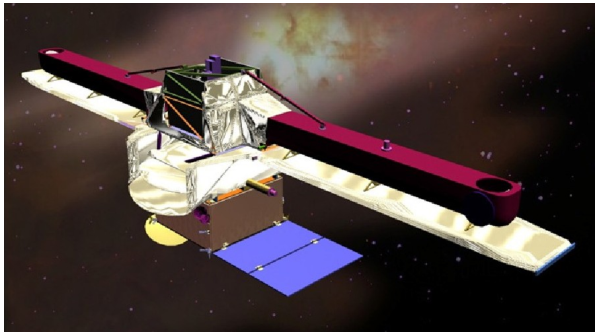
How to go deeper / cooler?

Absil et al. 2007; Defrère et al. 2008





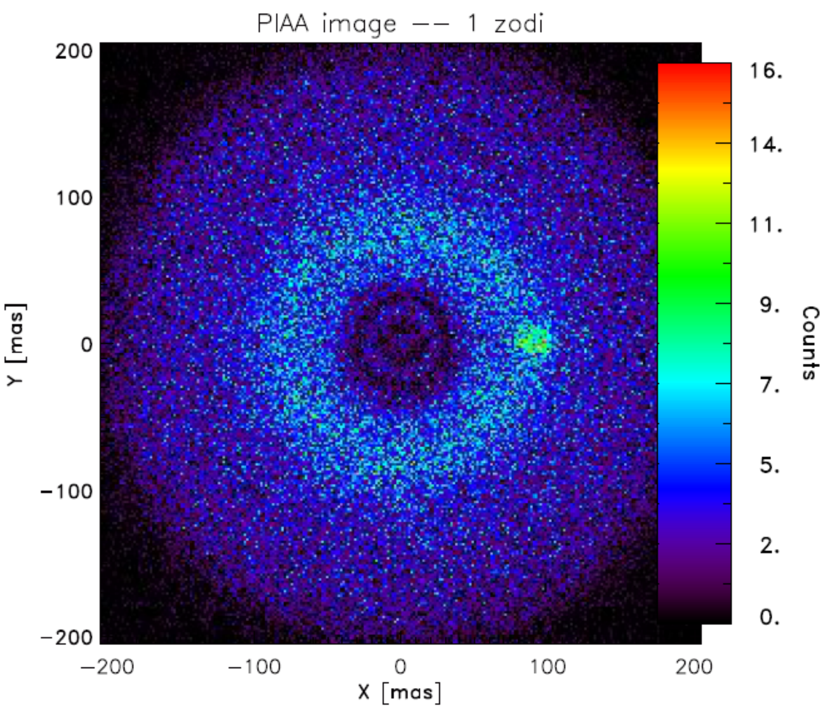


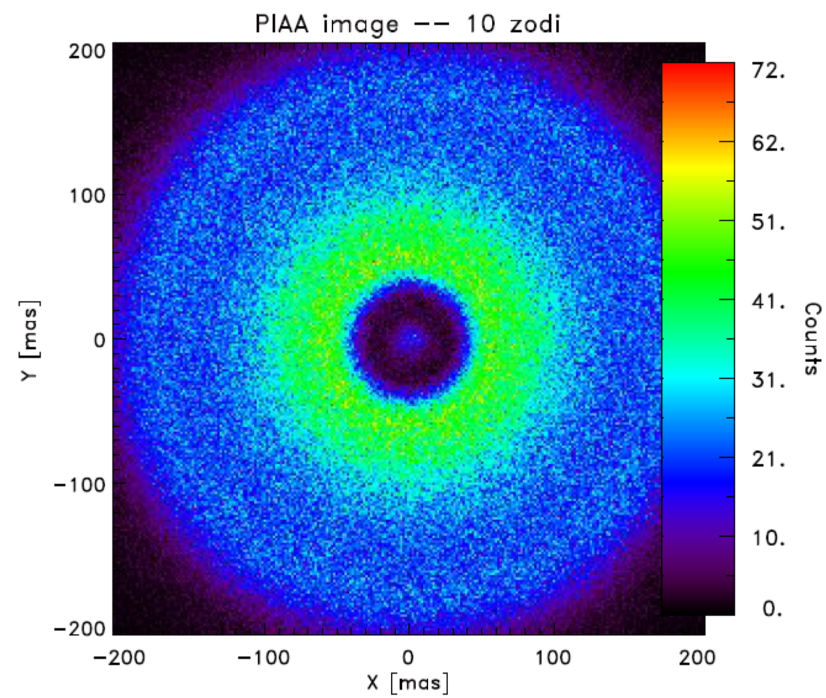


The 10-zodi limit

Defrère et al. 2012b

Sun-Earth system at 10 pc, seen by 4m space-borne coronagraphic telescope





Target sample selection

- Goal: no bias on inner/outer disk connection study
- One non-dusty "control" star for each dusty target
  - Same spectral type
  - Similar magnitude
  - Proximity on the sky
- No binaries, bloated stars
- Distribute evenly between A, F and G-K
- Final sample: ~100+100 stars (whole sky)