The Fomalhaut disk seen from every angle with interferometry

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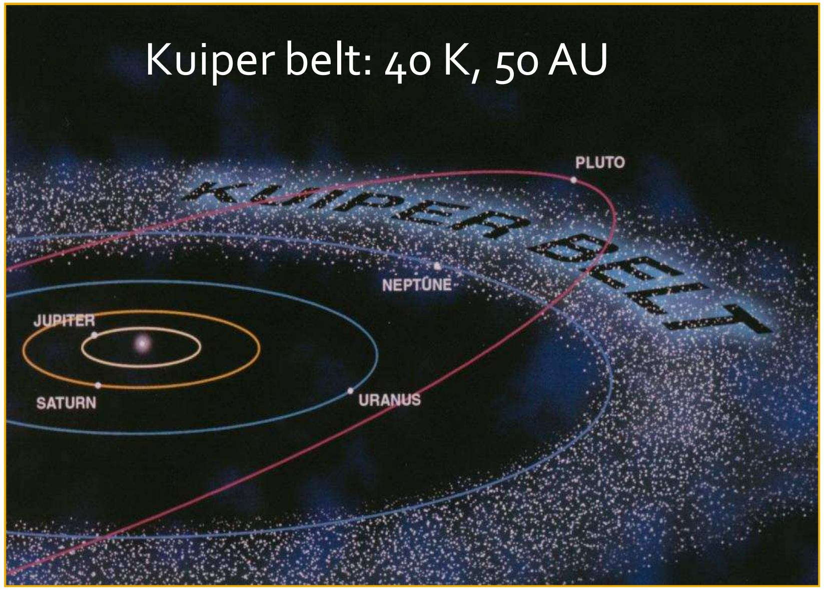
Dust in planetary systems

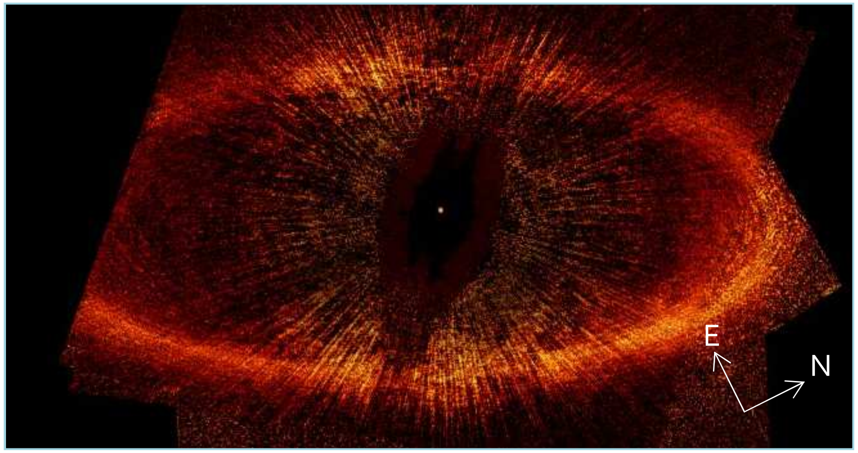
- We all live in a debris disk!
  - 2nd generation dust (asteroids, comets)
- Dust is luminous (**<u>much</u>** more than planets)
- Dust is expected in any planetary system



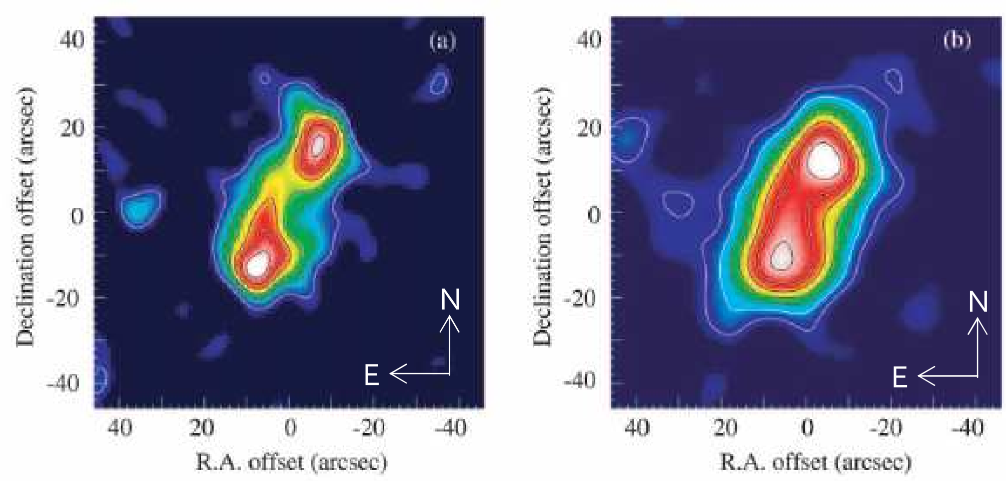
1 debris disk star, 3 studies

- Fomalhaut: A4V, 7.7 pc
- Debris disk resolved at various wavelengths
- VLTI/AMBER
  - Spin-orbit alignment of the debris disk
- VLTI/VINCI
  - Hot inner dust
- KI/Nuller
  - Warm inner dust

Kalas et al. 2005



Holland et al. 2003



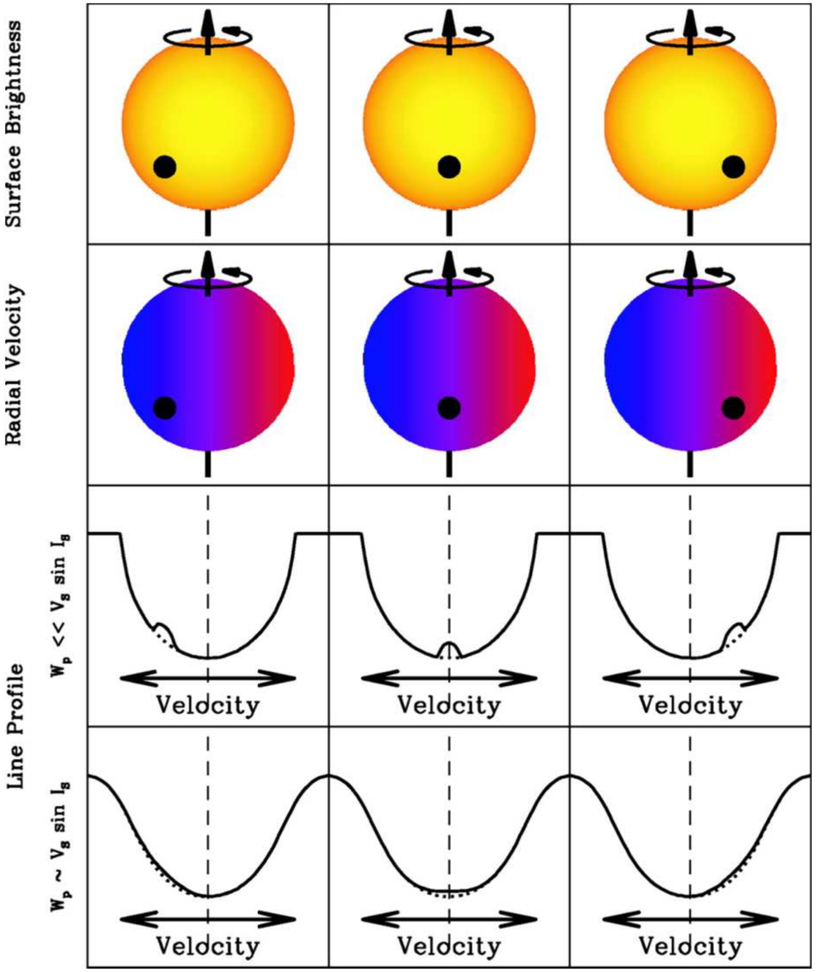
VLTI/AMBER

The Fomalhaut spin-orbit alignment

Le Bouquin et al. 2009

The Rossiter-McLaughlin effect

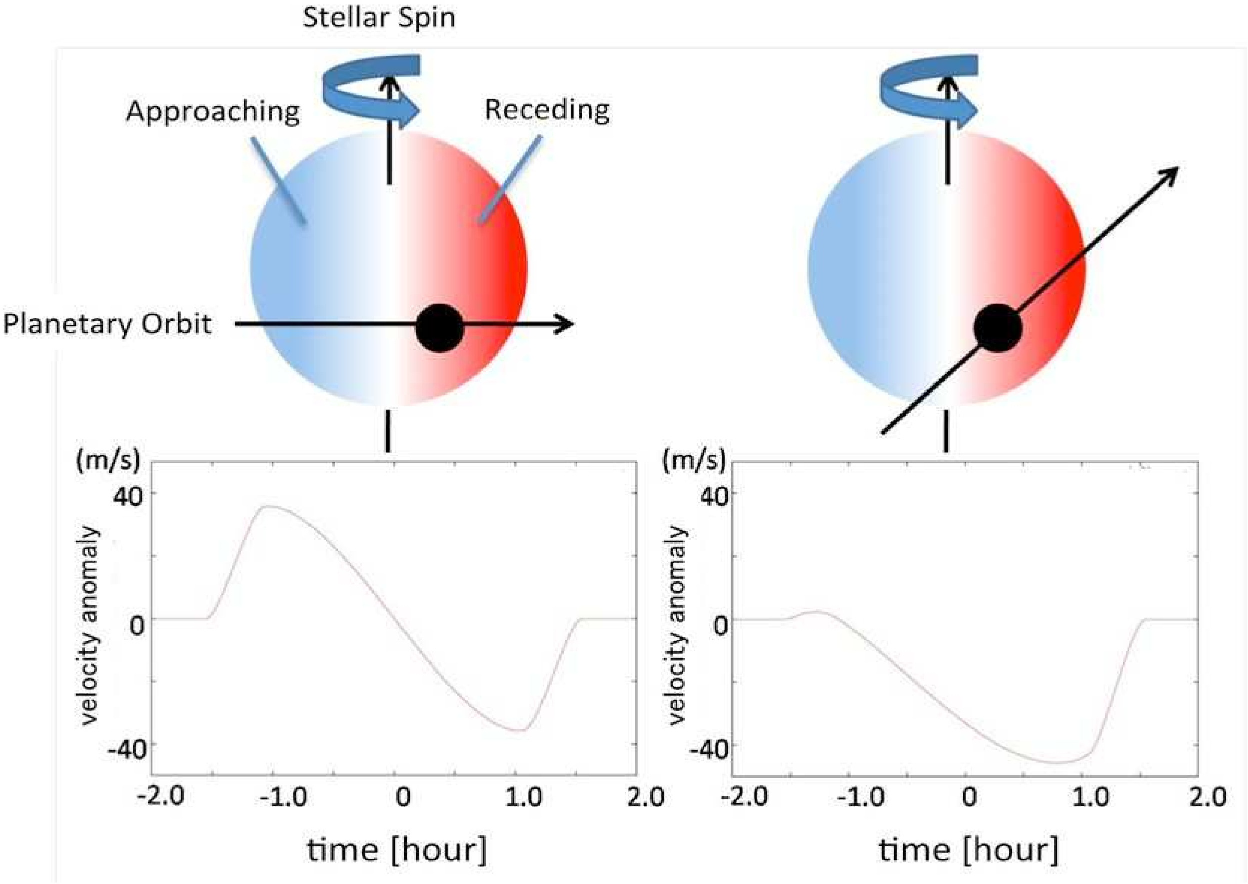
- Takes place during (planetary) transit
- Planet hides small fraction of one velocity component on photosphere
- Small bump moves through spectral line
- Creates RV anomaly



Gaudi & Winn 2007

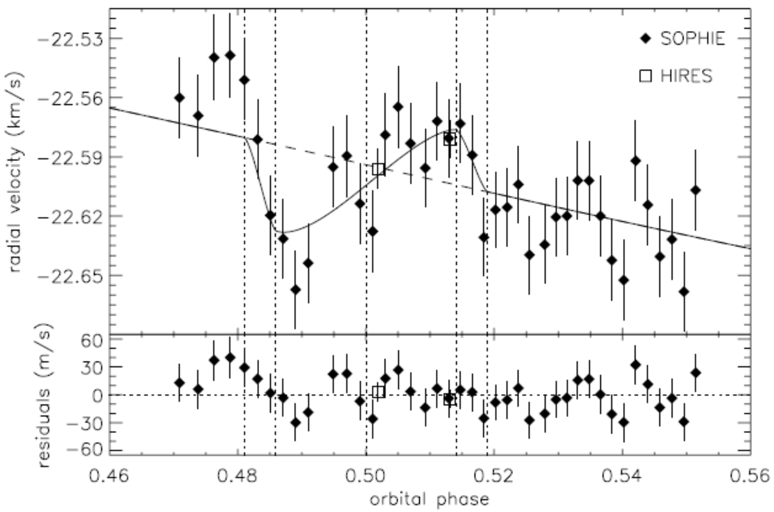
The Rossiter-McLaughlin effect

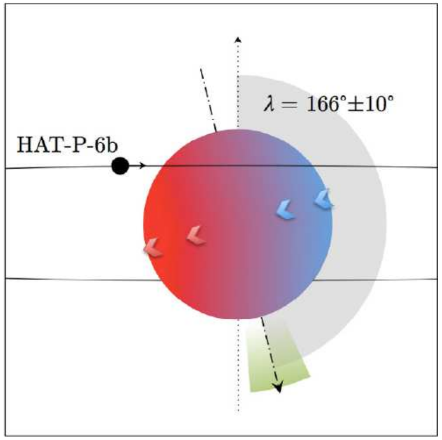
- Access to **projected** star/orbit inclination



RM detected for hot Jupiters

- First detection by Queloz et al. (2000)
  - HD 209458b aligned
- 40 systems observed
  - 18 significantly misaligned
  - 9 on retrograde orbits
- Detection not easy
  - Significant error bars (~10°) on relative inclination



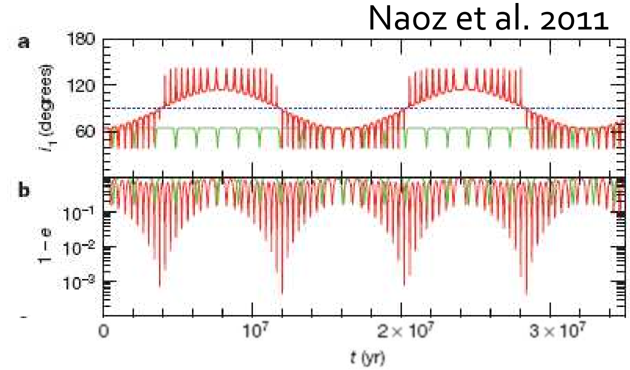


Example: HAT-P-6b
(Hébrard et al. 2011)

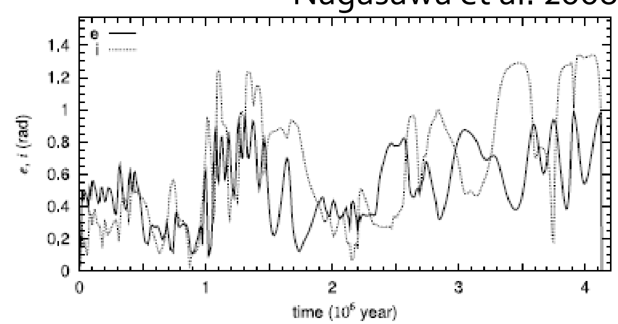
Possible explanations

- Disk-driven migration not possible
- Kozai mechanism
  - Requires distant 3rd body on inclined orbit (40° < i < 140°)
  - Secular oscillations of eccentricity and inclination for inner planet
  - Circularisation by tidal friction
- Planet-planet scattering
  - Instabilities in multiple (packed) planetary systems
  - Orbit crossing → high eccentricities / inclinations
  - Circularisation by tidal friction

Naoz et al. 2011

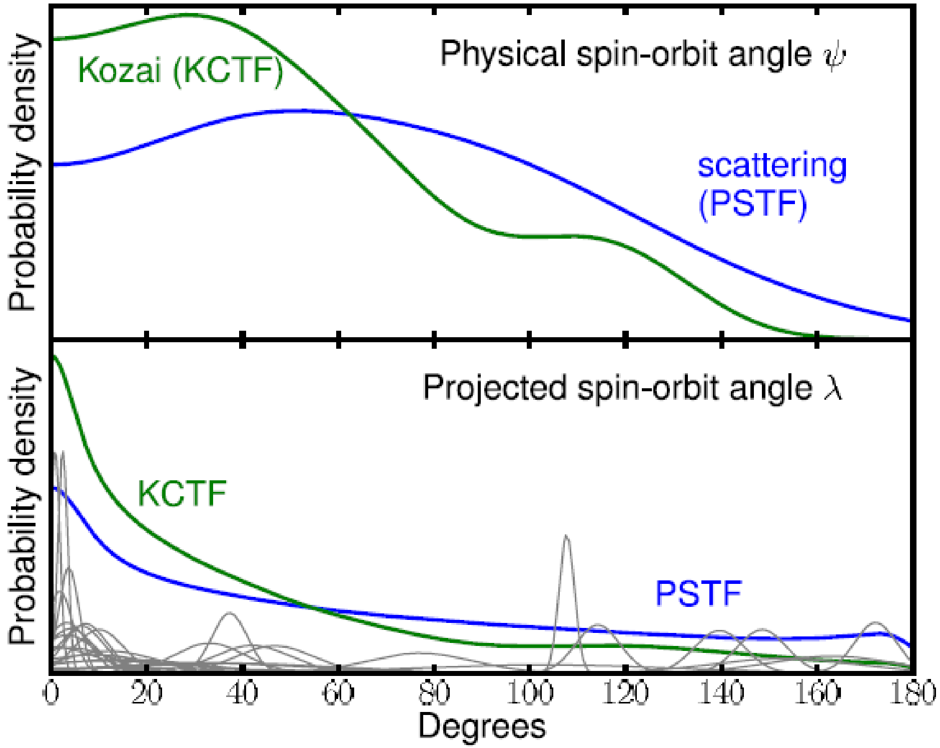


Nagasawa et al. 2008



Kozai or scattering?

- Strongly debated issue (Morton & Johnson 2011)
  - Need 2× more observed systems to conclude



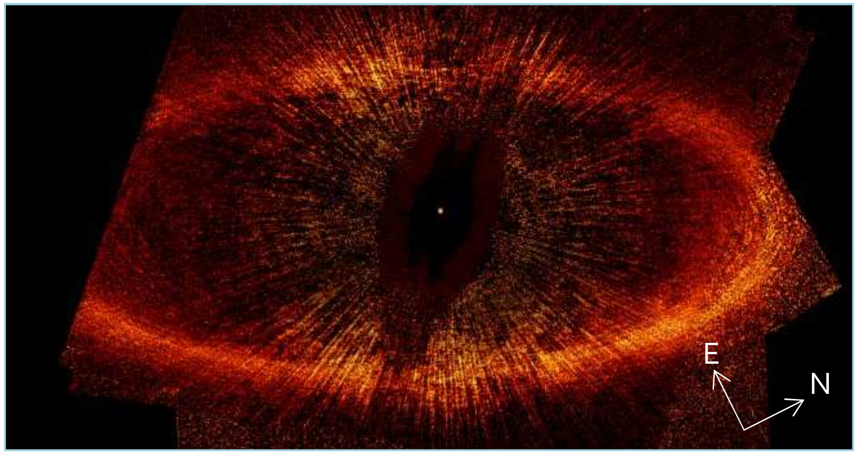
Alternative scenarios

- Misalignment may date back to proto-planetary disk phase
- Early stellar encounter (Bate et al. 2010)
  - Stellar cluster → chaotic environment
  - Interactions → misalignment + truncation
    - Enough mass left for planets?
- Magnetosphere-disk interactions (Lai et al. 2011)
  - Magnetic protostar exerts warping/precessional torque on disk inner region
  - Disk resists warping → back-reaction torque

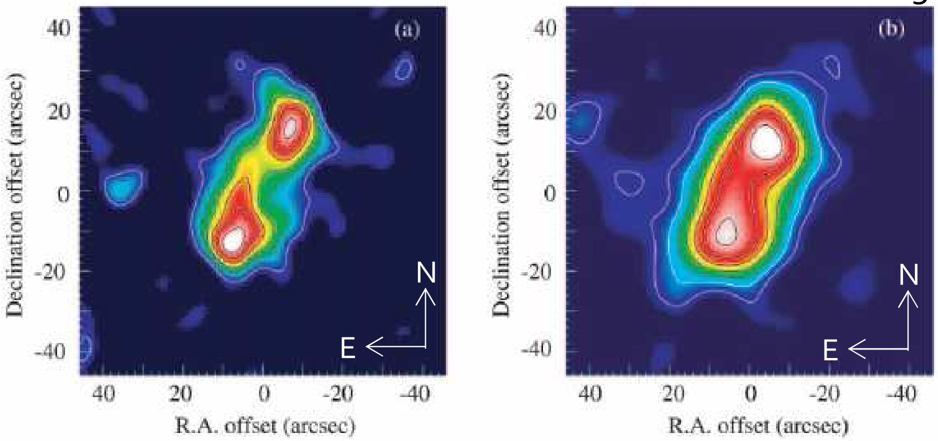
How to discriminate?

- Use debris disks
  - ~25 have been resolved
  - More with Herschel
- Resolved image
  - Inclination / position angle easy to measure
  - Materialises the plane of planetary formation
- Need stellar orientation

Kalas et al. 2005



Holland et al. 2003

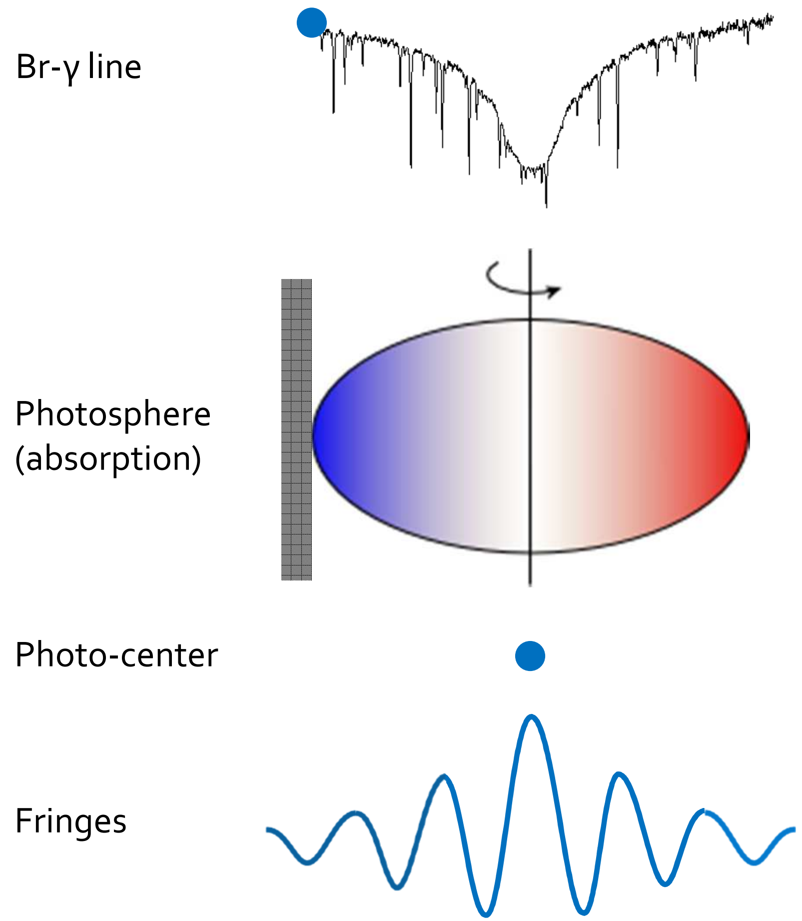


How to get stellar orientation?

- Inclination from $P_{rot} \times v \sin i / 2\pi R_*$ (Watson et al. 2011)
  - P_{rot} from photometry or Ca II lines (low precision)
  - $v \sin i$ from high resolution spectroscopy
  - R_* from spectra, interferometry, …
  - Result: no misalignment in 8 systems (FGK stars)
    - BUT: final error bars generally ≥ 10°
- Position angle from spectro-interferometry
  - Only for rapidly rotating stars (A / early F)
  - Subject of this talk

PA from spectro-interferometry

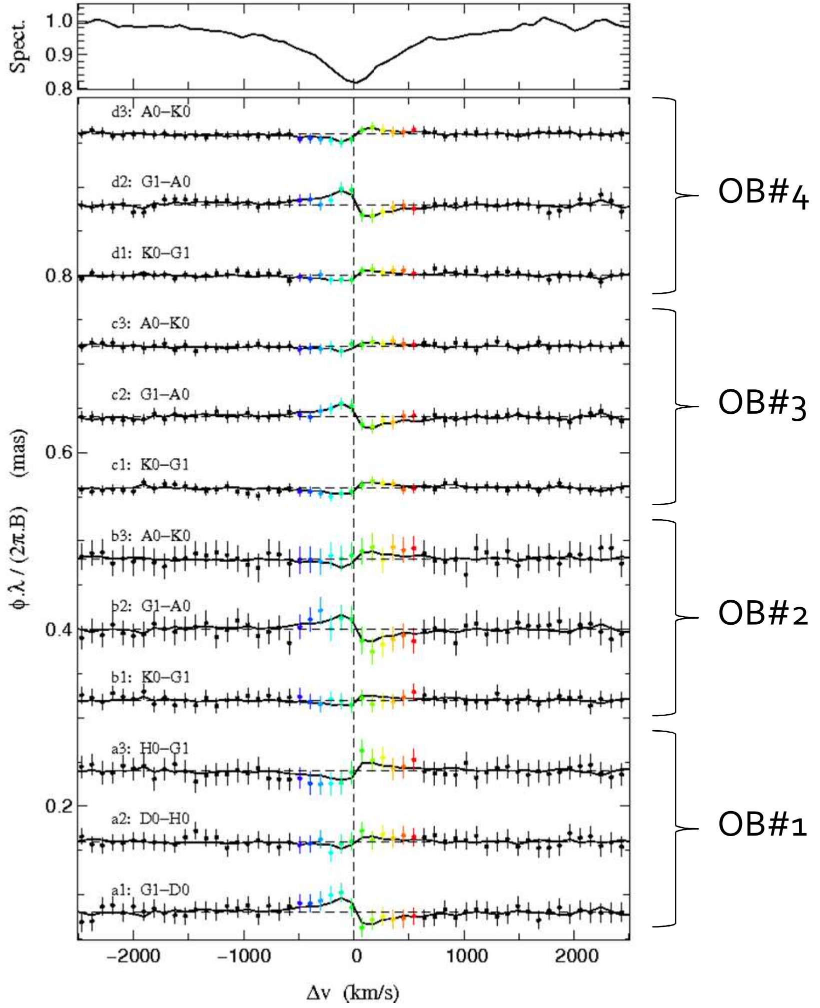
- Requirements
  - Rapidly rotating star
  - Deep absorption line
  - Partly resolved photosphere (≥ 1 mas)
- Displacement of photocenter across the Br-γ line
  - Signature in fringe phase versus wavelength
  - 2D phase → position angle



Fomalhaut with VLTI/AMBER

- AMBER
  - 3 × Auxiliary Telescopes
  - Baselines: ~100m
  - Medium spectral resolution (R=1500) in K band
- Fomalhaut
  - v sin i = 93 km/s
  - Angular diam: θ = 2.2 mas
- Measure wavelength-differential phase
  - Deduce 2D differential astrometry

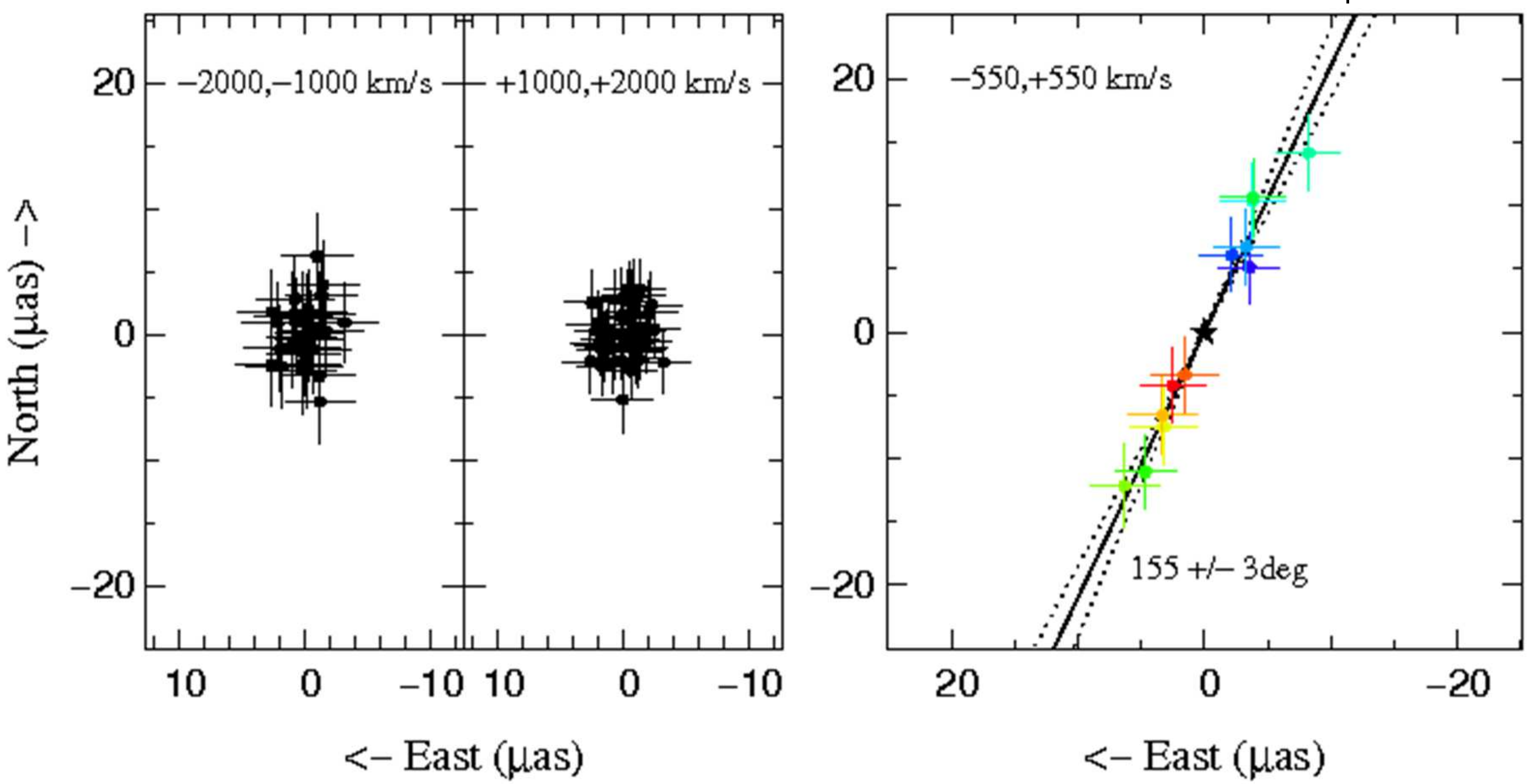
Le Bouquin et al. 2009



2D differential astrometry

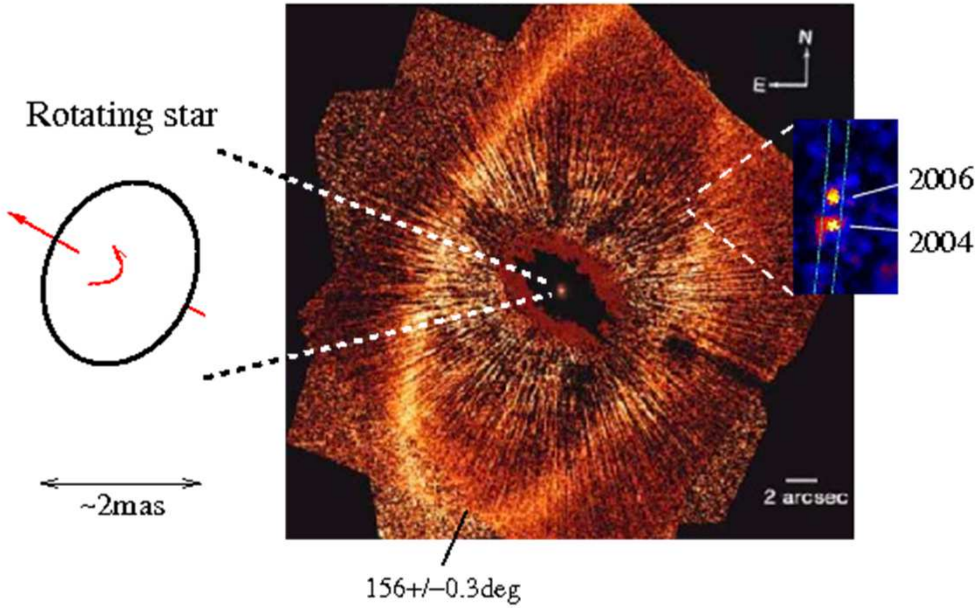
- Clear signature inside Br-γ line
  - Precision: ~3 µas

Le Bouquin et al. 2009



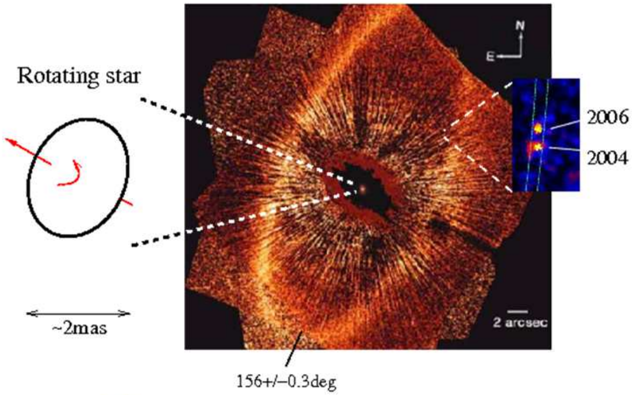
Spin-orbit alignment

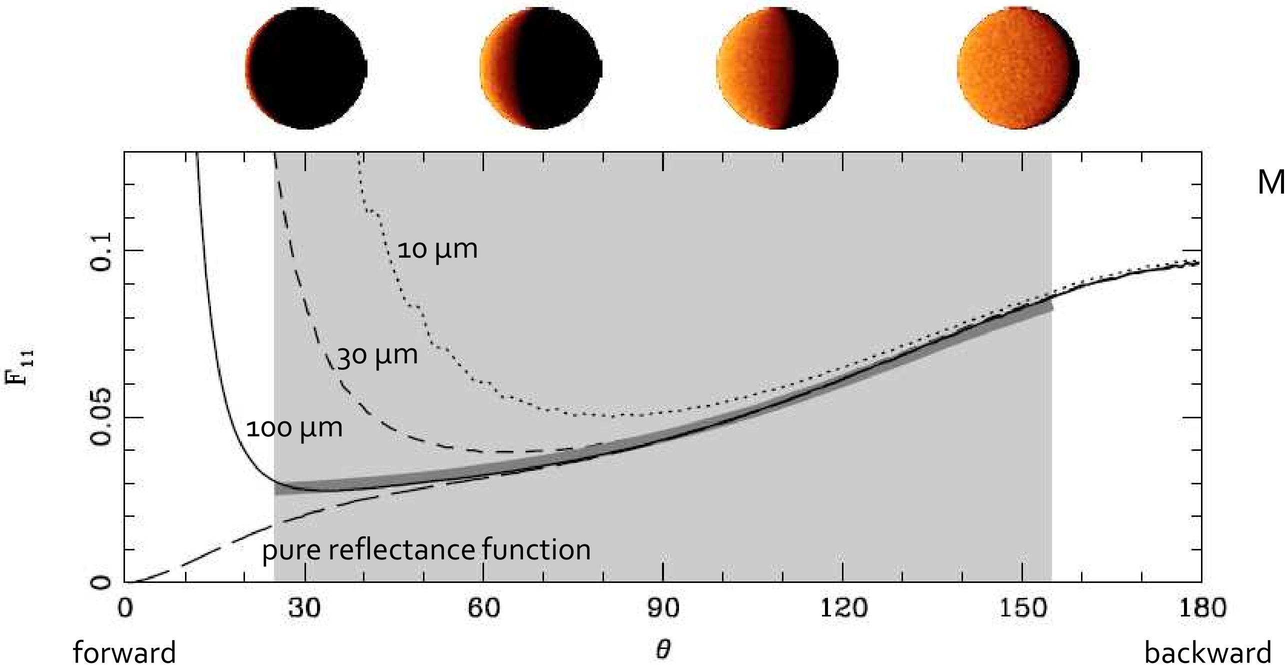
- Photosphere position angle: 155° ± 3°
  - But inclination not constrained (needs advanced model)
- Disk position angle: 156.0° ± 0.3°
- By-product: discriminate front side / back side
  - Assuming planet prograde and stellar spin not flipped



Backward scattering dominant?

- Possible only with big grains
  - Similar to lunar phases
- Small grains ejected?
  - What about further collisions?





Min et al. 2010

VLTI/VINCI

Searching for hot dust in the Fomalhaut inner disc

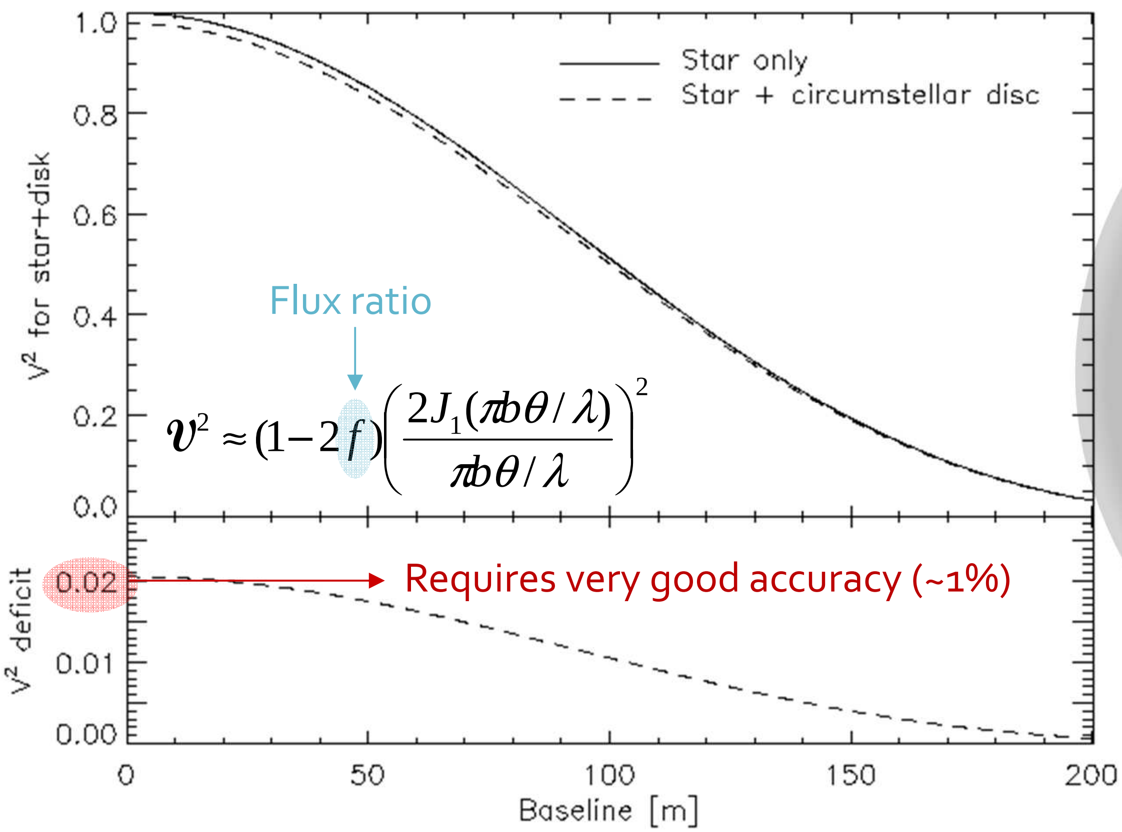
Absil et al. 2009

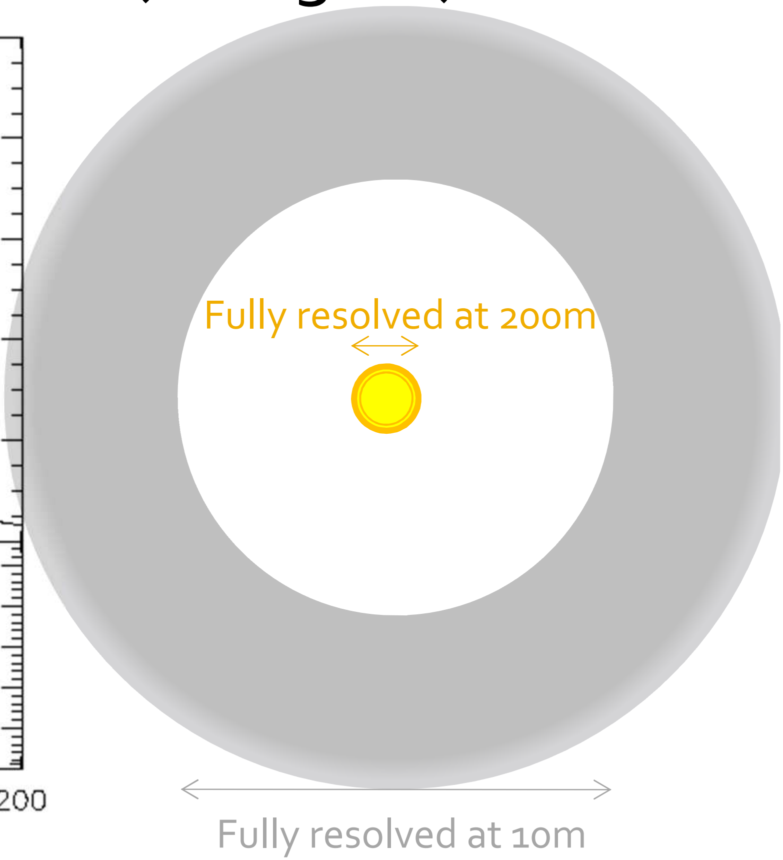
Context

- Exozodiacal discs poorly known
  - Small angular separation (< 100 mas)
  - High contrast (> 1:100)
- Fomalhaut: unresolved 24μm excess
  - Suggests warm compact component
- Goal: search for K-band excess
  - Method already demonstrated with CHARA/FLUOR

Principle of exozodi detection

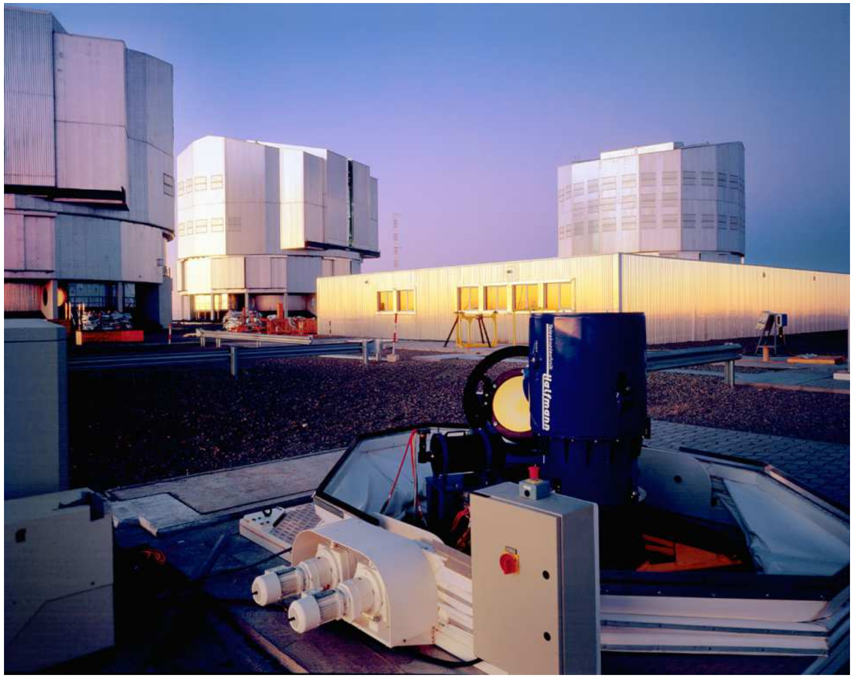
- Disk larger than λ/B → visibility loss
- Best detected at short baselines (~10-30m)





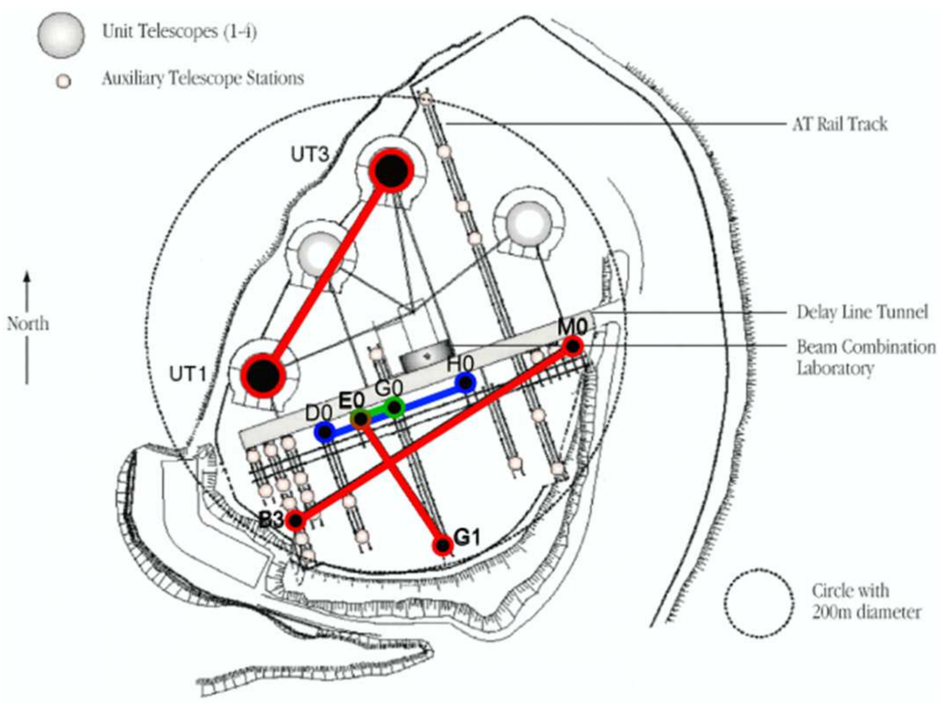
The VINCI instrument

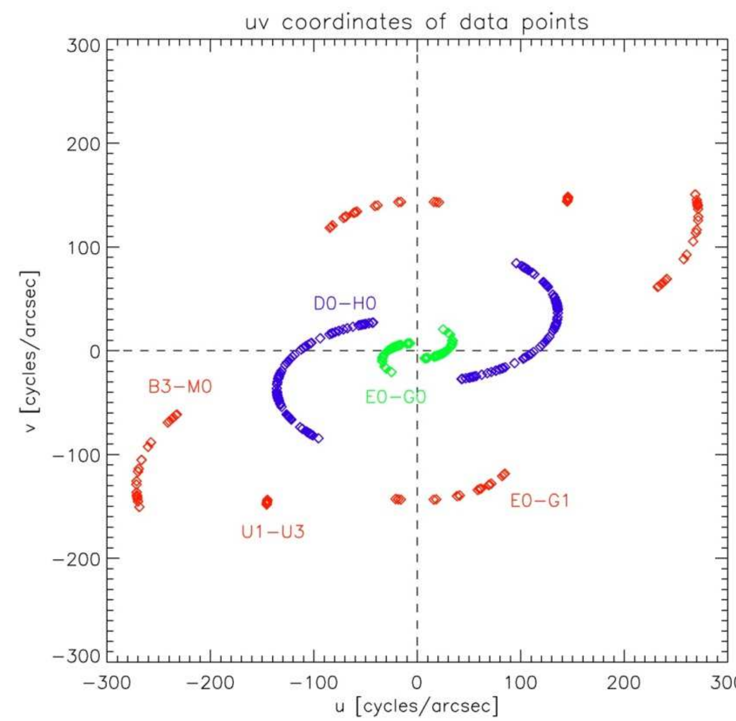
- Operated at VLTI in 2002-2004 as test instrument
- Conceptual copy of FLUOR at CHARA
  - Beam combiner based on single-mode fibers
  - Dedicated photometric outputs
- Mostly working on 30-cm siderostats



Fomalhaut observations

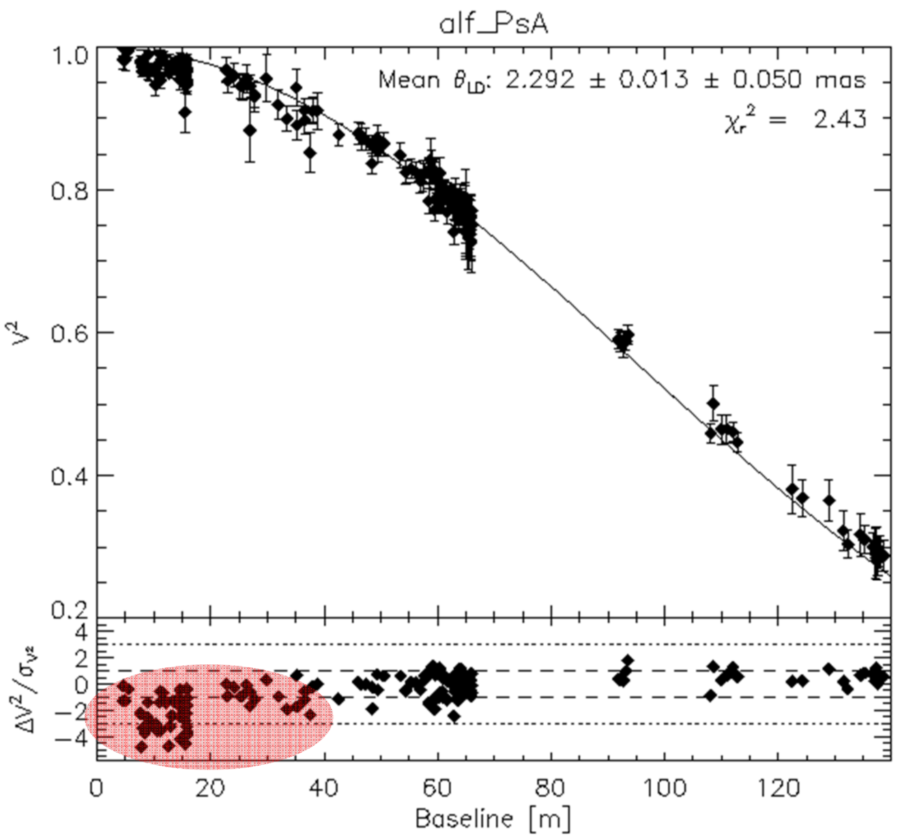
- Available in ESO archive
  - Baselines: short (~10m) to long (~100m)



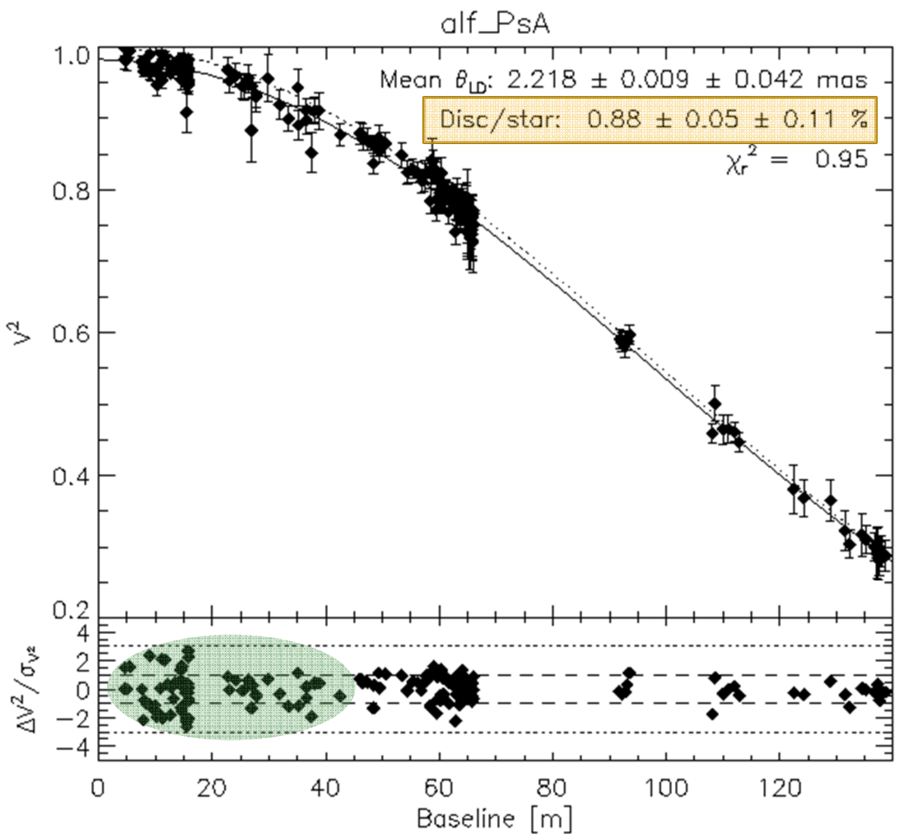


Fitting the data

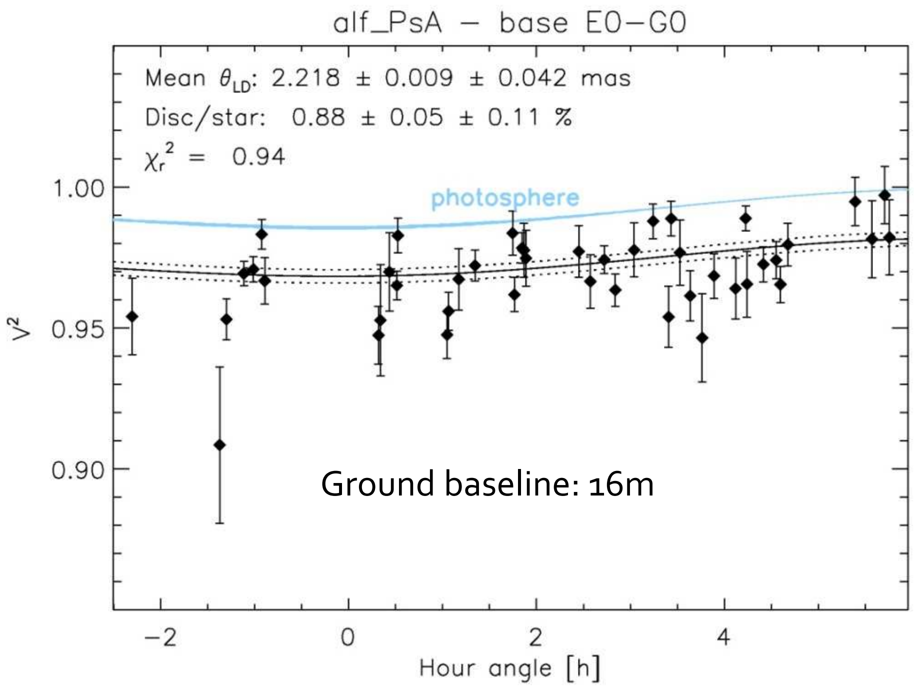
Oblate limb-darkened photosphere

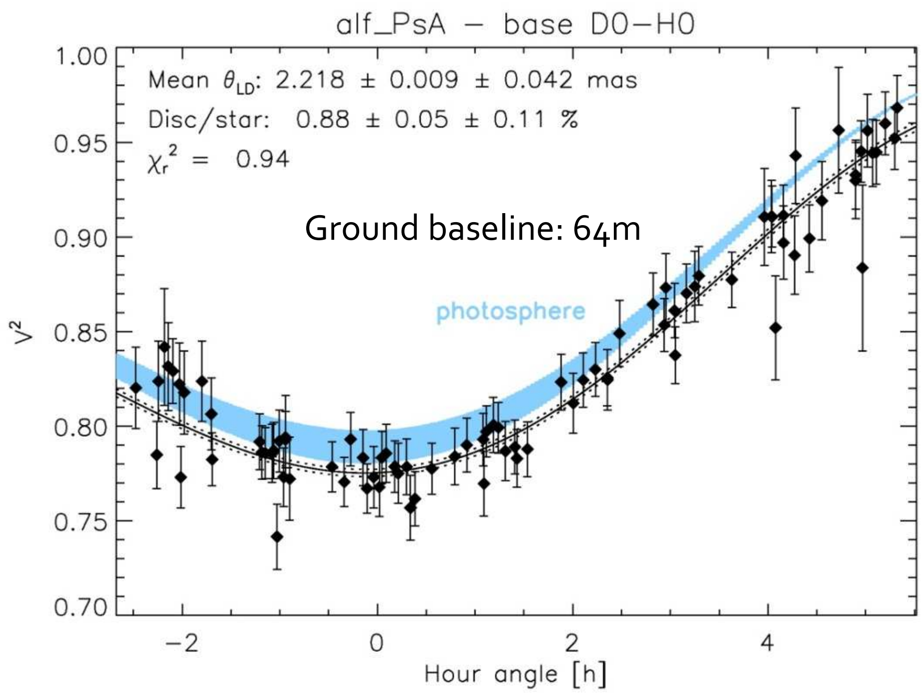


Photosphere + uniform circumstellar disk



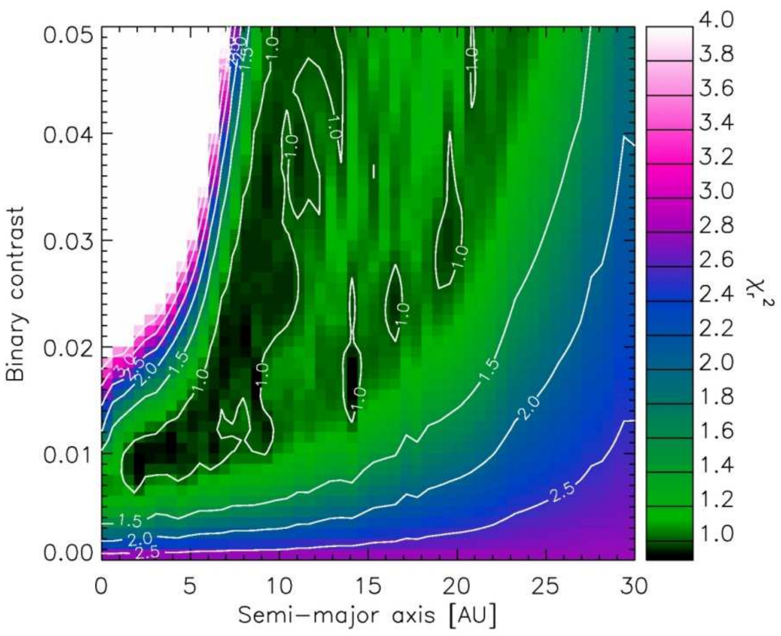
Zoom on short baselines

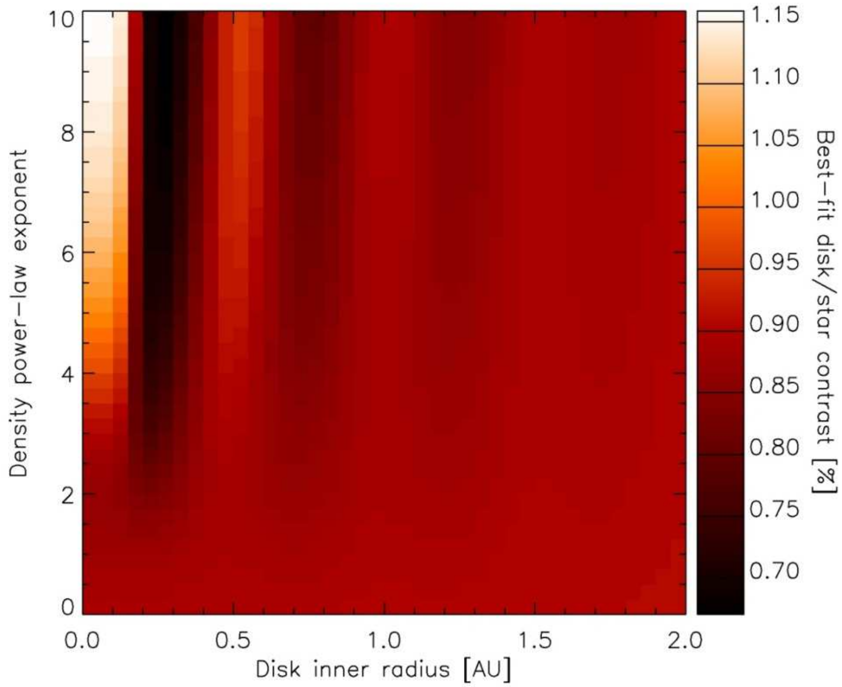




Morphology of the excess

- Can range from uniform disk to point-like
  - Due to lack of observing strategy
- Has weak influence on best-fit contrast



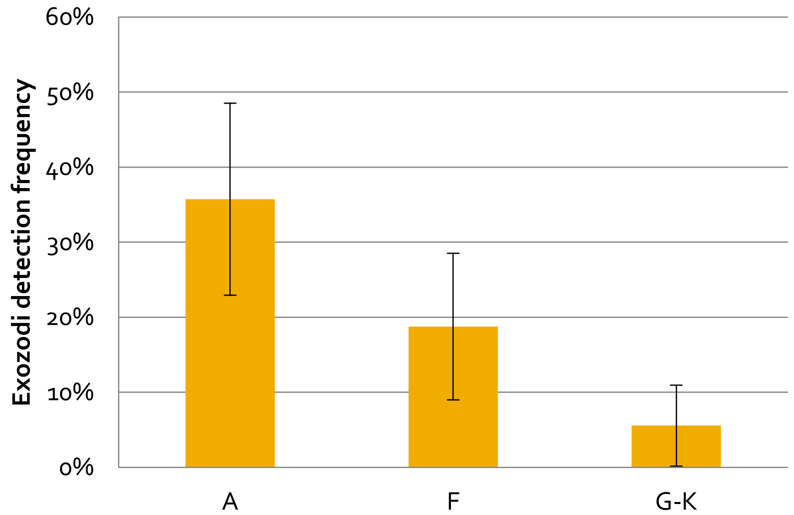


Possible sources of near-IR excess

- Point-like source?
  - RV and astrometry stable → no companion
  - VLTI/PIONIER: no companion > 0.3% within 100 mas
  - Very low probability for background star
- Stellar wind / circumstellar gas?
  - A stars: very weak winds (~$10^{-12..14}$ $M_\odot$/yr)
  - Ae/Be phenomenon: no evidence for Hα emission
- Circumstellar dust?
  - Thermal emission & reflected flux
- New, unknown phenomenon?

What can we conclude from VINCI?

- Excess emission of 0.88% on FOV ~ 1″
- Assuming zodiacal disk model
  - Fractional luminosity: $L_{disk} / L_{star} \sim 5 \times 10^{-4}$
  - 5000 × density
  - Could reproduce 17-24μm excess (Spitzer/IRS and MIPS)
- Not an isolated case
  - On-going survey with CHARA/FLUOR
  - ~10 excess / 50 stars



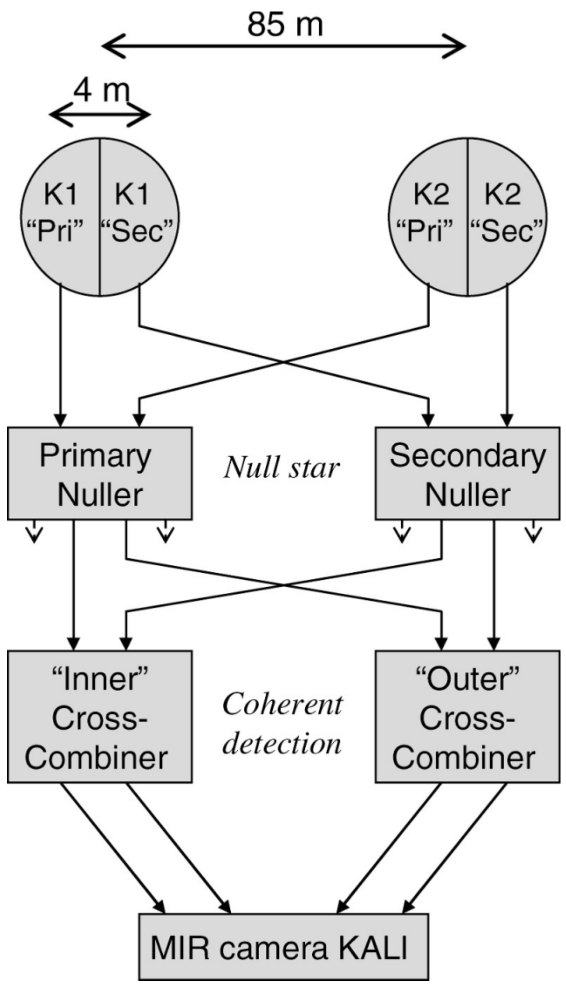
KI/Nuller

Further constraints on the Fomalhaut inner disk

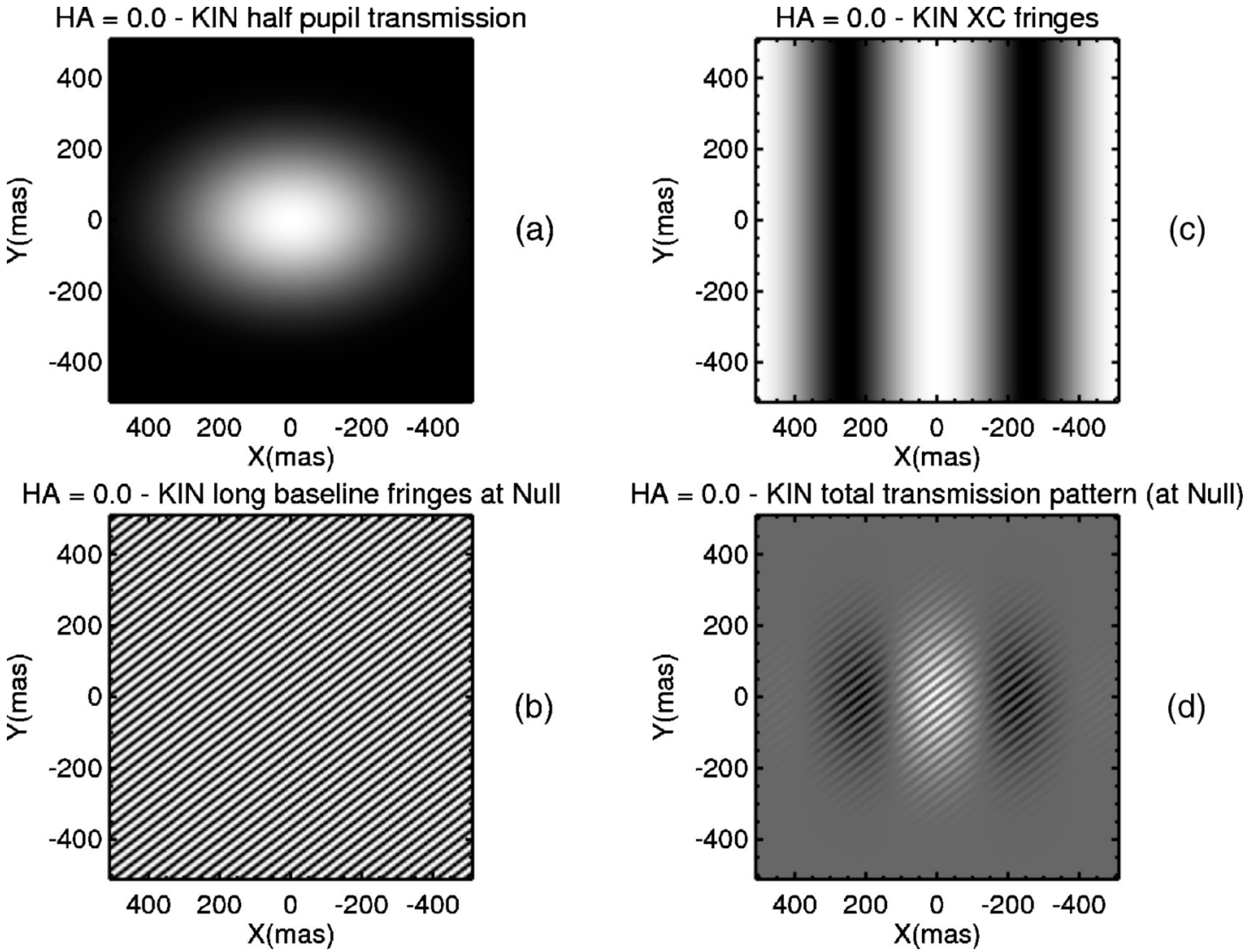
Mennesson et al., in prep

Keck Interferometer Nuller (KIN)

- Mid-infrared nulling on 85m baseline
  - Inner working angle ~ 10 mas
- 2nd stage combination on 4m baseline
  - Background subtraction by modulation
- Low resolution spectro
- Accuracy: 0.2% on null

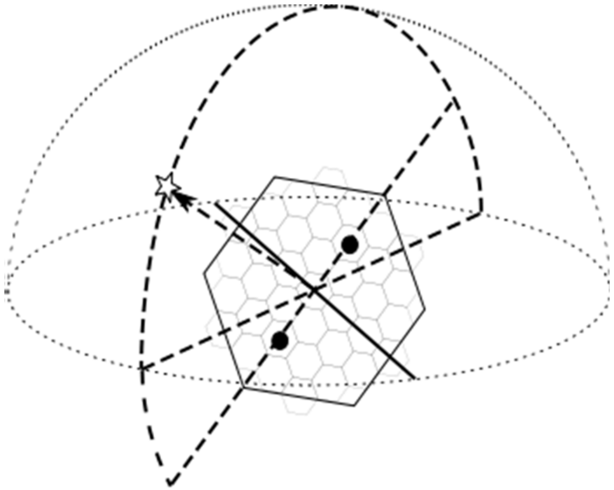


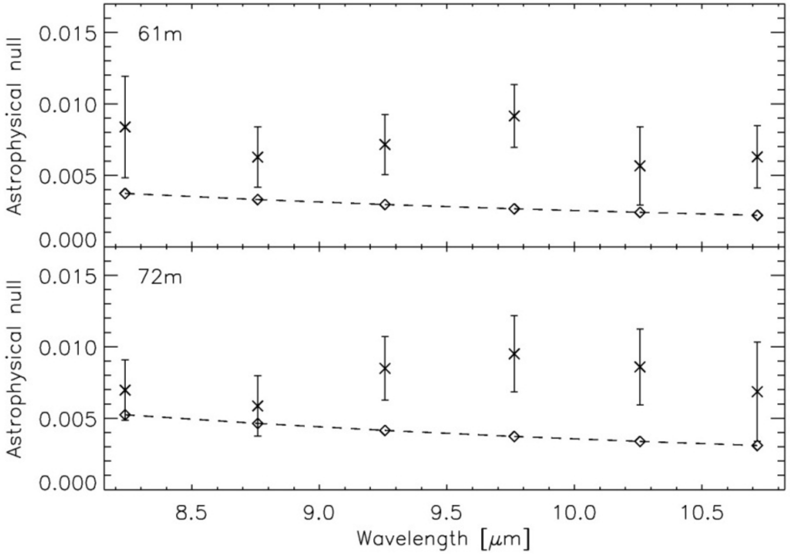
KIN transmission map

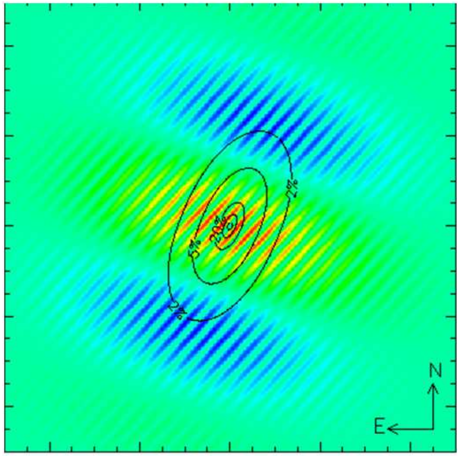


The 2007 data set

- 6 observations (2 nights)
  - 8 to 11 µm
- Separated into two subsets
  - Short projected baselines (~61 m)
  - Long projected baselines (~72 m)

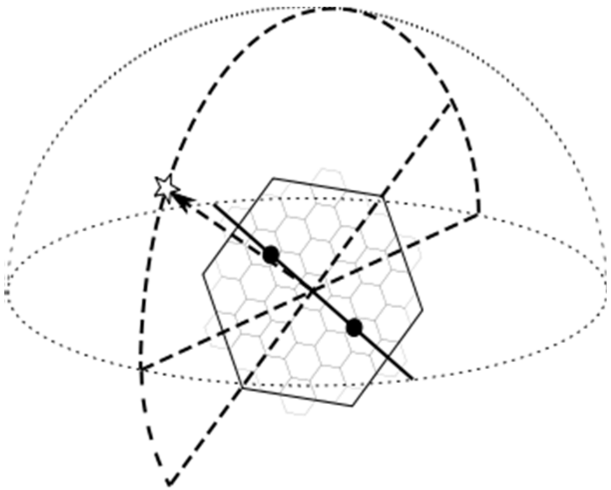


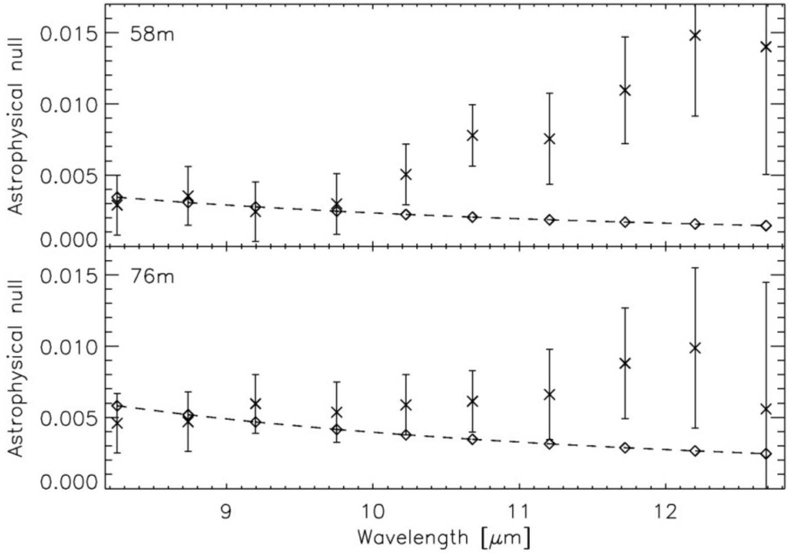


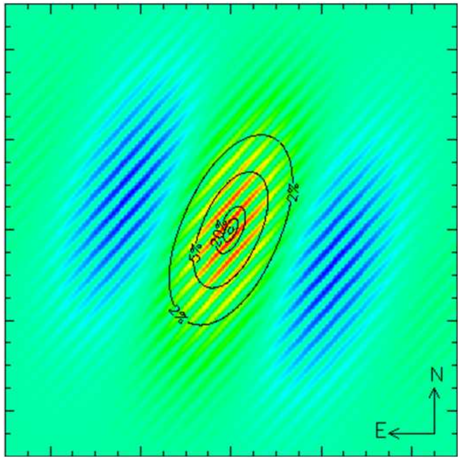


The 2008 data set

- 8 observations (2 nights)
  - 8 to 13 µm
- Separated into two subsets
  - Short projected baselines (~58 m)
  - Long projected baselines (~76 m)

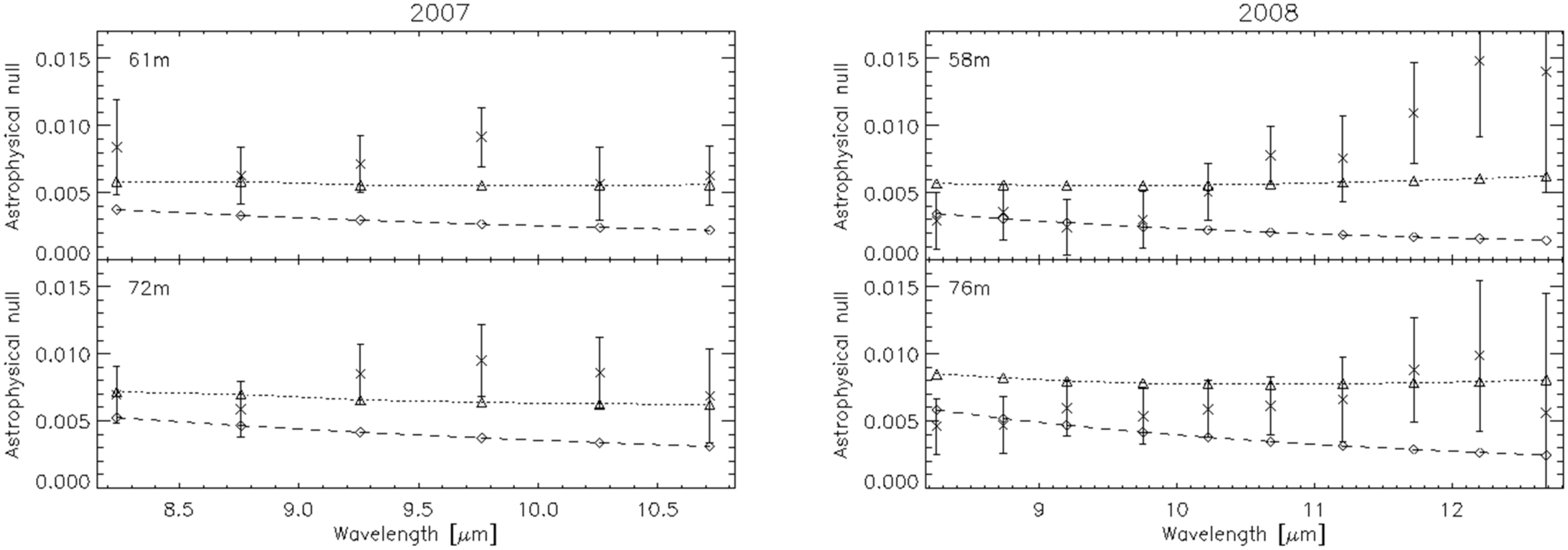






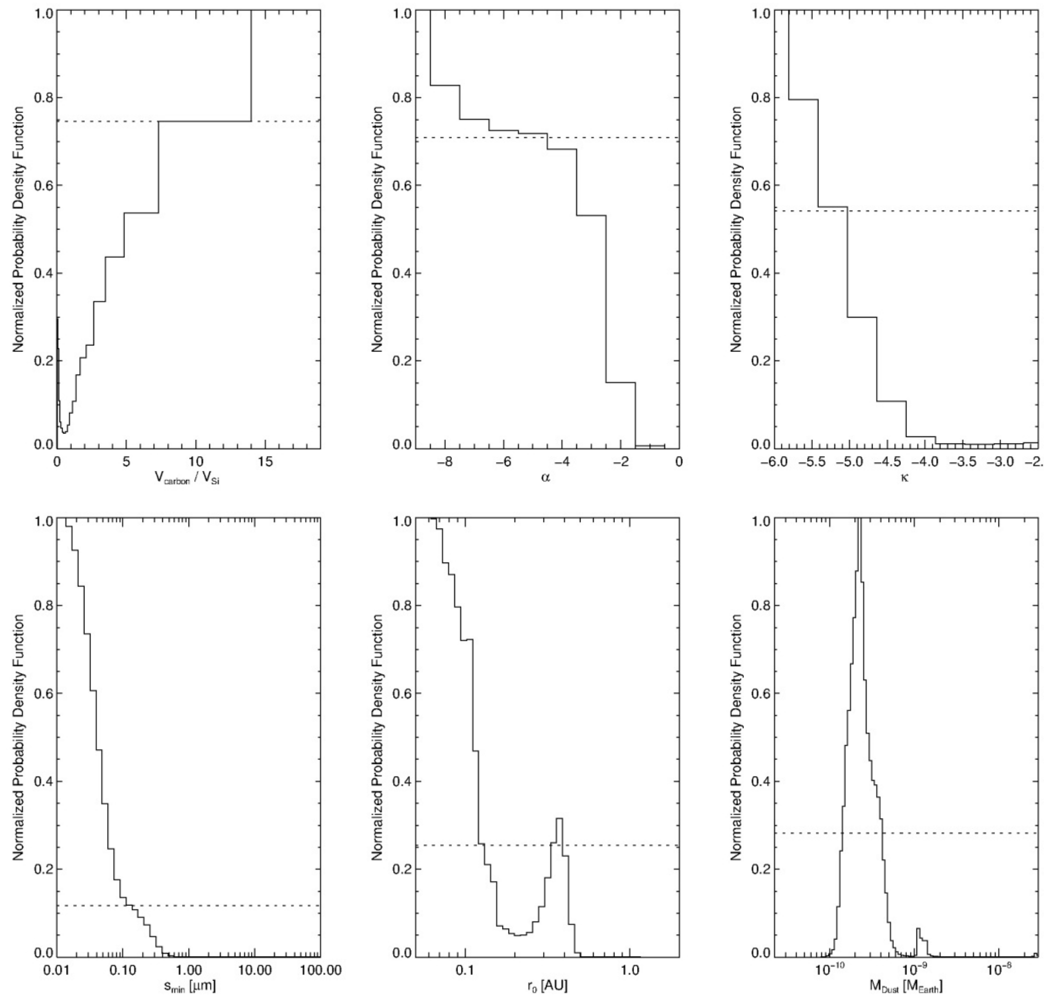
Fitting KIN with solar zodi model

- Marginal null excess (0.26% ± 0.1%)
  - Corresponds to about 250 zodi of dust
- Solar zodi not representative of dust distribution



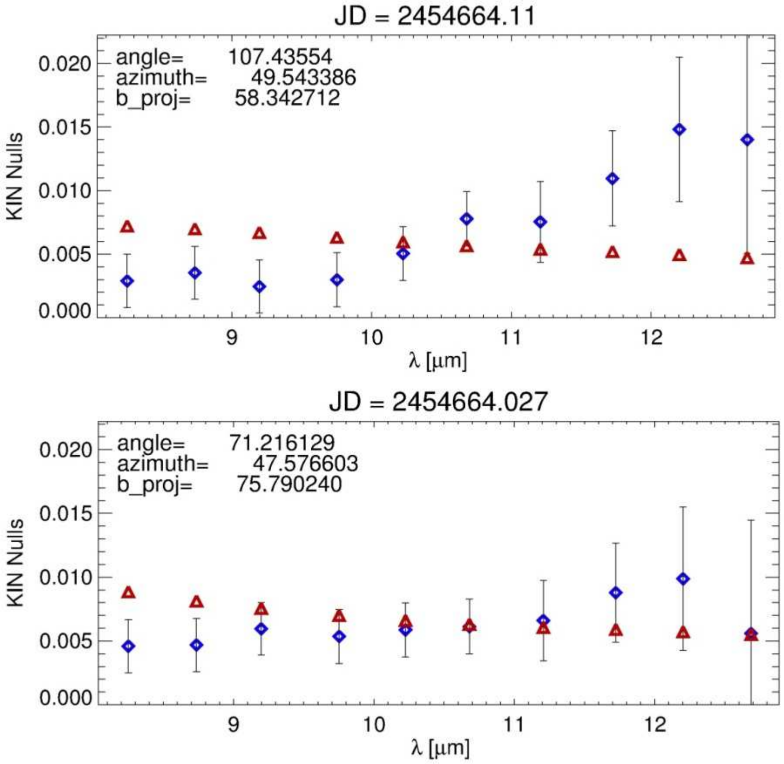
Fitting KIN and VINCI

- Compute χ^2 for large set of disk models
- Use Bayesian analysis for all parameters
- Reveals very compact disk of hot and small dust grains

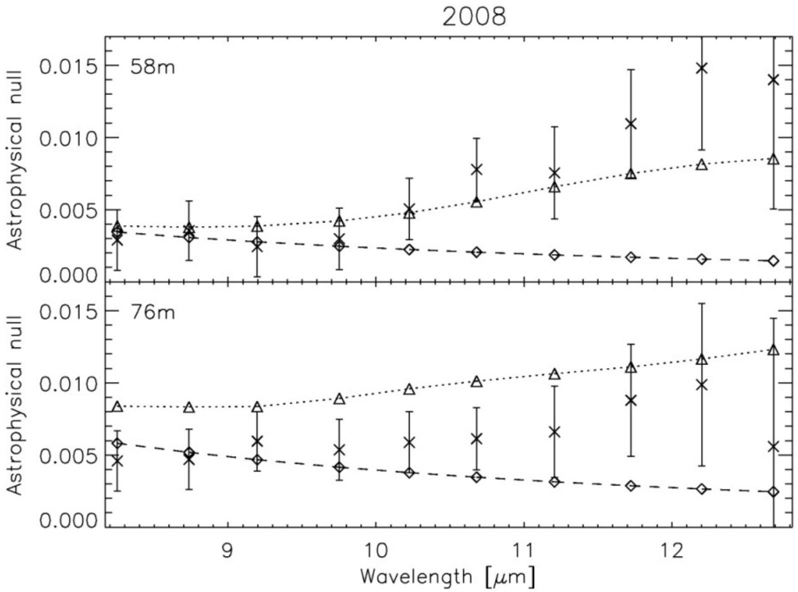


Two-component disk?

Best fit from Bayesian analysis



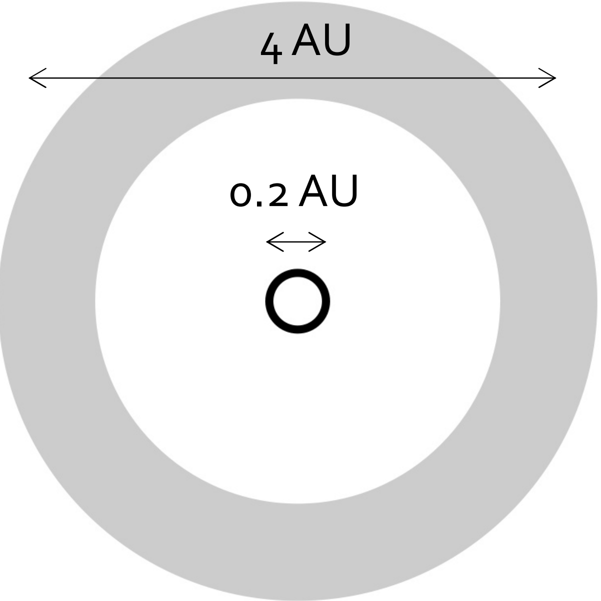
Ring from 1.5 to 2 AU



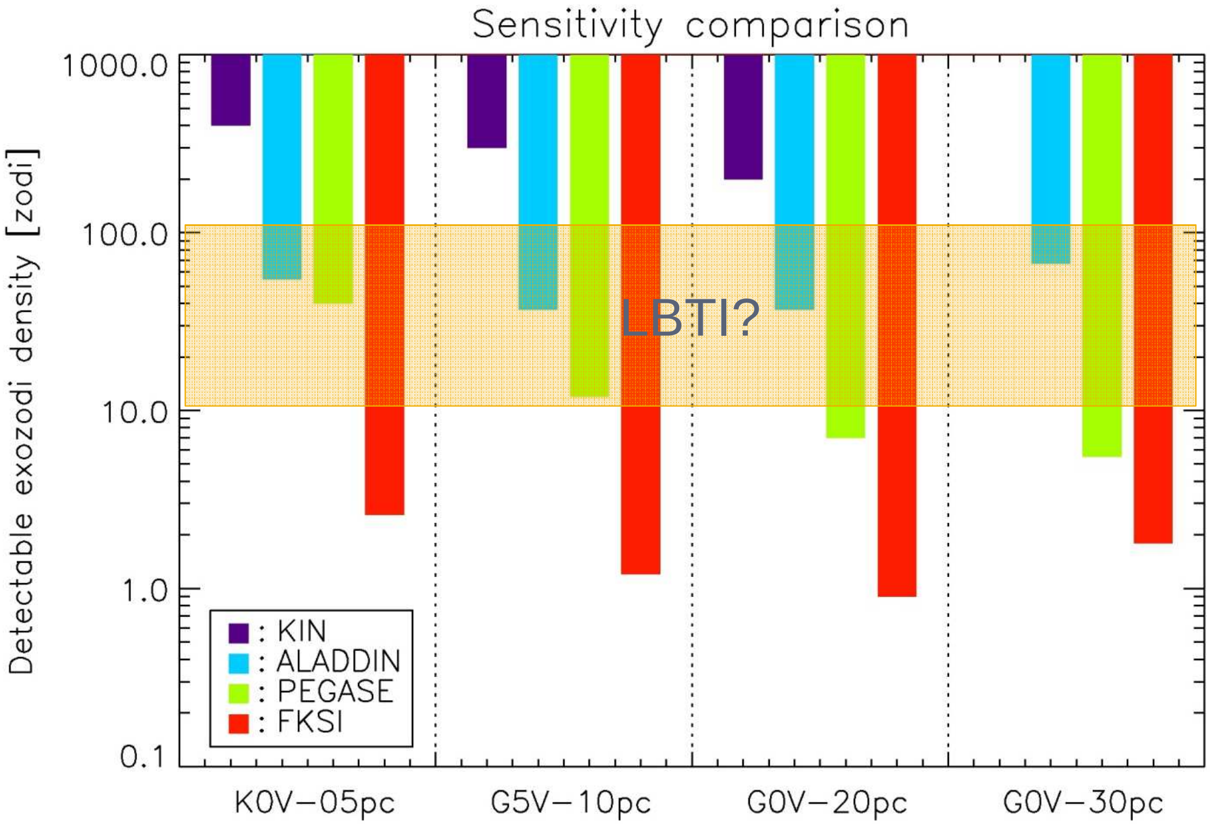
Could also reproduce unresolved Spitzer excess from 17 to 24μm

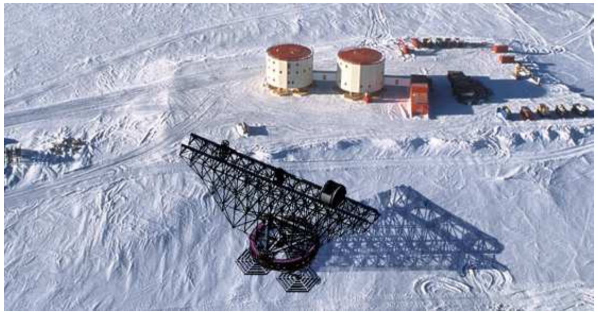
Possible scenarios?

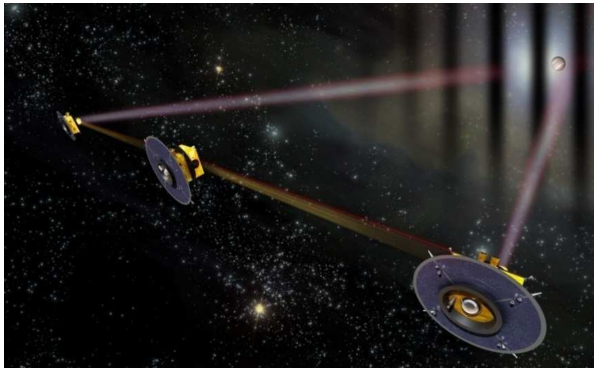
- Inner ring
  - Dust released by evaporating comets in an LHB-like shower?
  - Trapped nanoparticles?
- A gap created by a planet?
  - Must be < 1 Mjup (RV stable)
- Outer ring
  - Could be a « standard disk » released by parent bodies around 1.5-2 AU

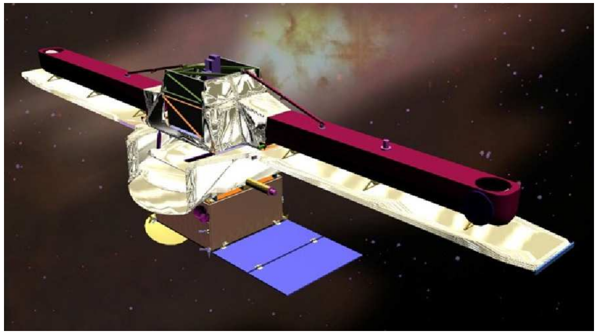


How to go deeper?









Conclusions

- Debris disk in equatorial plane of Fomalhaut
  - Unexpected consequences on grain properties!
- K-band excess
  - Suggests large amount of hot dust
- Small N-band excess null
  - Not compatible with a solar-like zodi
  - Possible explanations
    - Much more compact disk (trapped nano grains?)
    - Variability between 2003-2004 and 2007-2008?
  - Source of Spitzer 24µm excess possibly resolved

Fomalhaut with VLTI/PIONIER

- Detection limits based on closure phases
  - 7 OBs in total (~2h)
  - 7 spectral channels within K band