The spin-orbit alignment of the Fomalhaut debris disk

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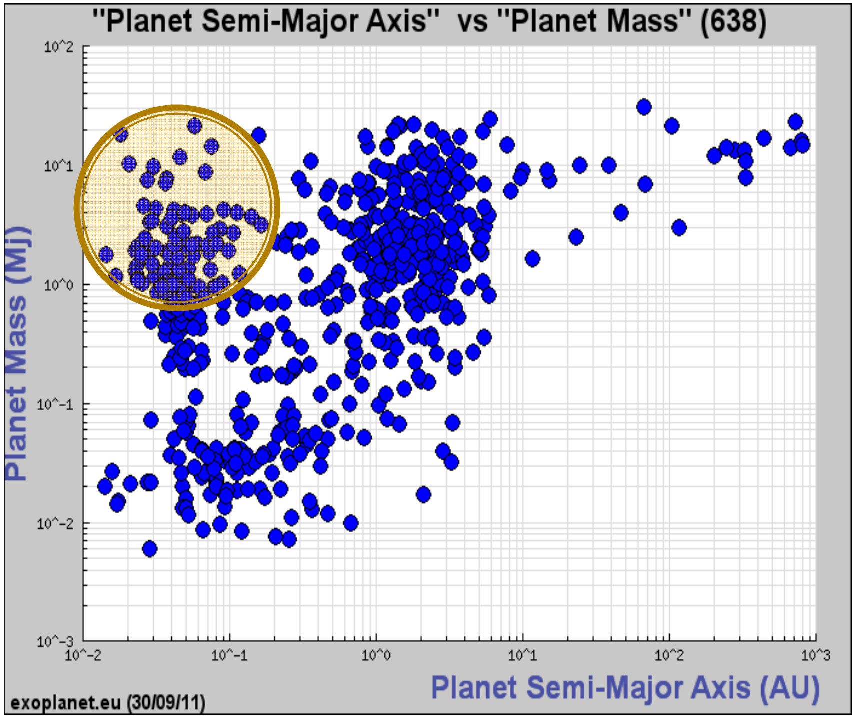
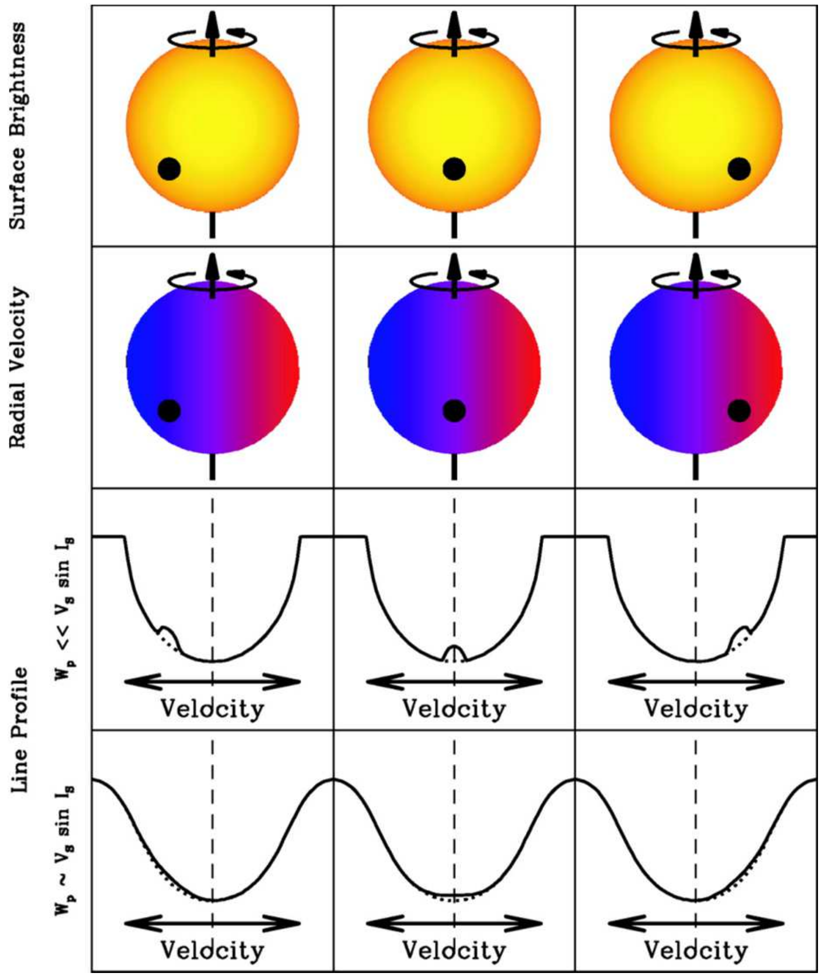
Exoplanets galore

- 600+ exoplanets discovered so far
  - Many more unconfirmed Kepler candidates
- « Hot Jupiters » are most emblematic
- Planetary transits
  - Radius
  - Composition
  - Spin-orbit orientation



The Rossiter-McLaughlin effect

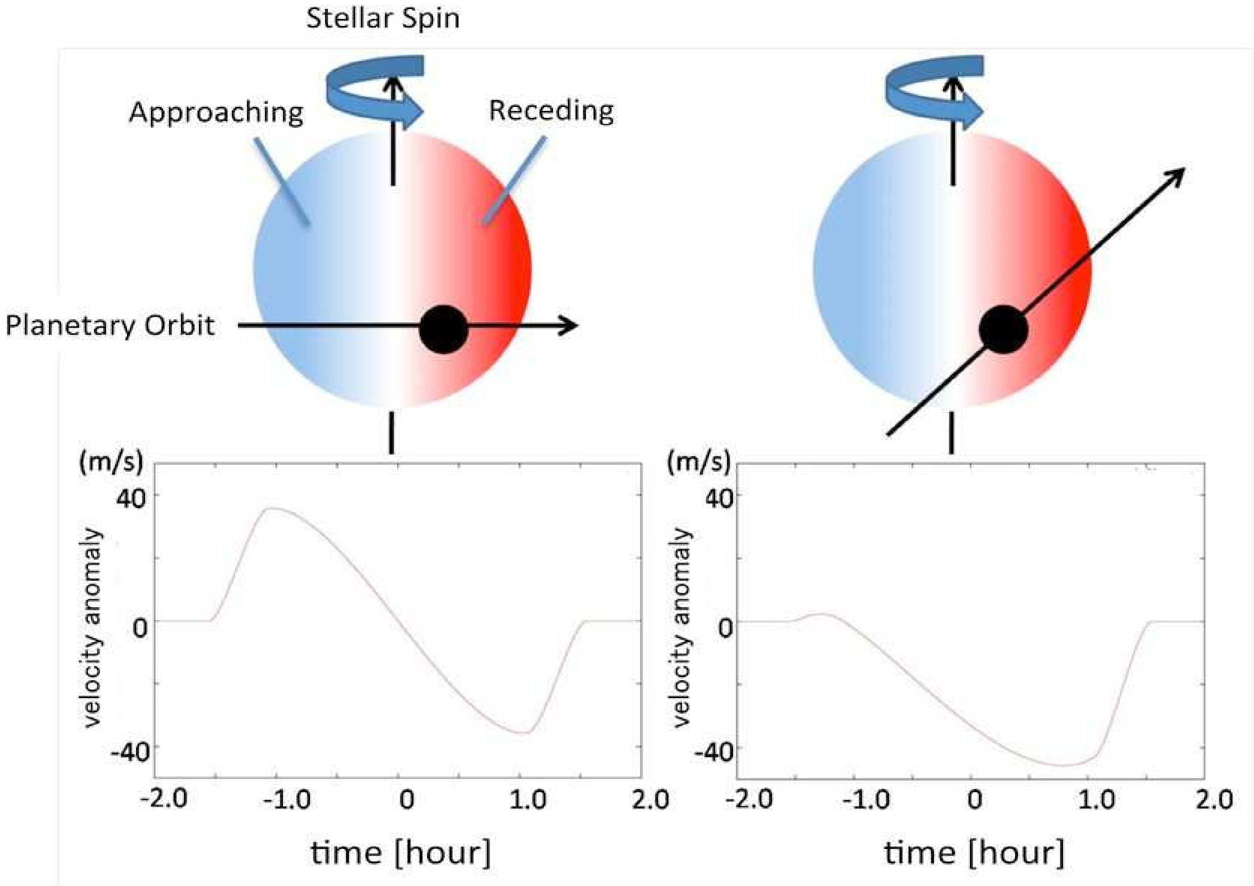
- Takes place during (planetary) transit
- Planet hides small fraction of one velocity component on photosphere
- Small bump moves through spectral line
- Creates RV anomaly



Gaudi & Winn 2007

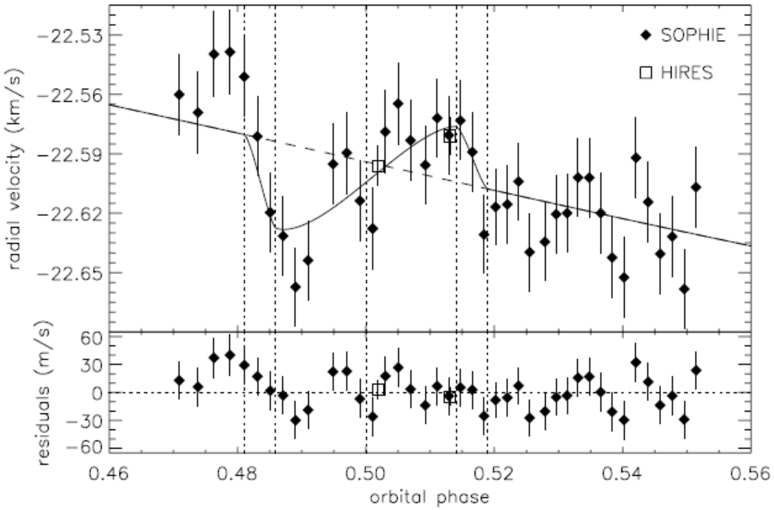
The Rossiter-McLaughlin effect

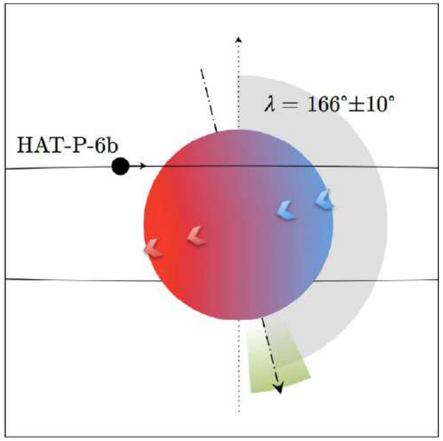
- Access to **projected** star/orbit inclination



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



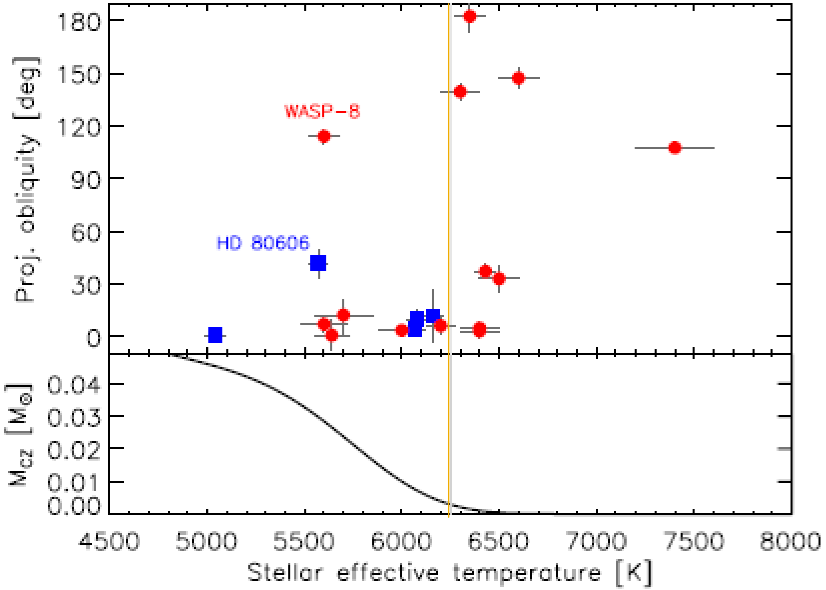


Example: HAT-P-6b (Hébrard et al. 2011)

First statistical trends

- Misalignments more frequent for hot stars (>6250K)
  - Due to tidal dissipation in stellar convective zone?
  - Exceptions: light planets and long periods
- Most hot Jupiters may have « arrived » misaligned

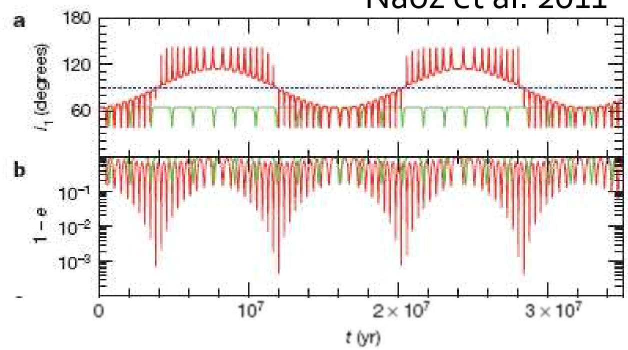
Winn et al. 2010



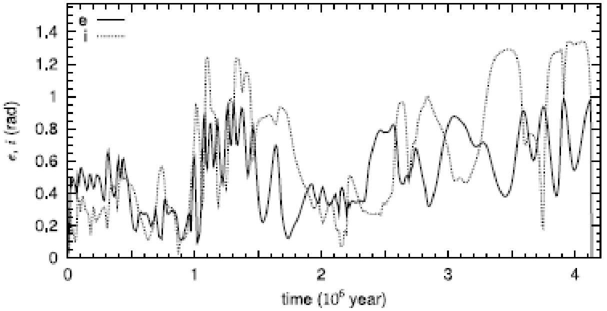
Possible explanations

- 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

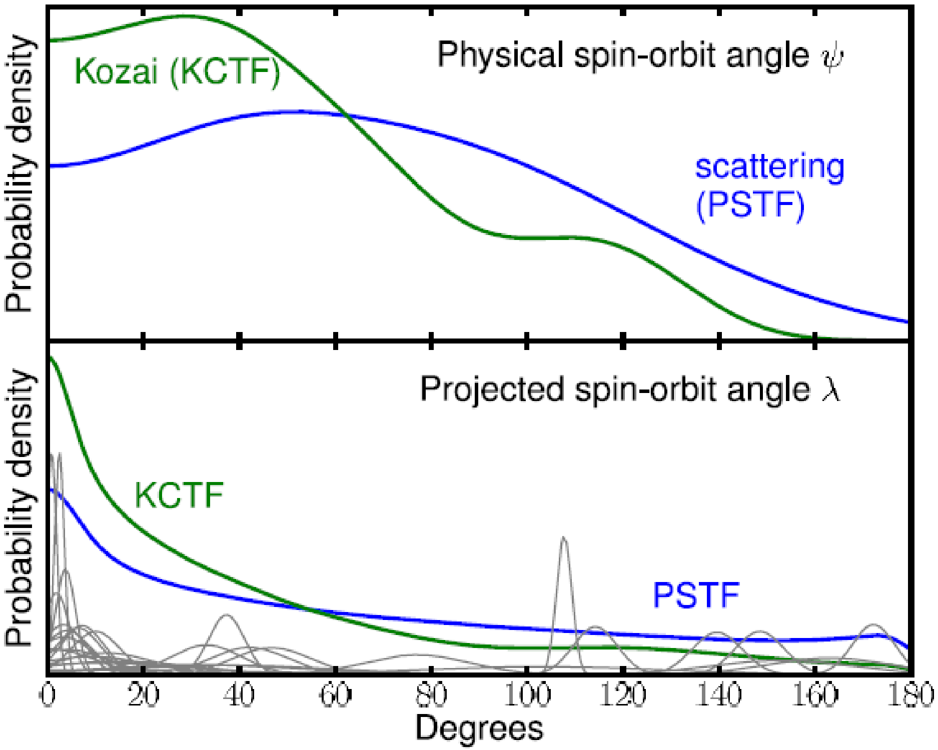


Nagasawa et al. 2008



Kozai or scattering?

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

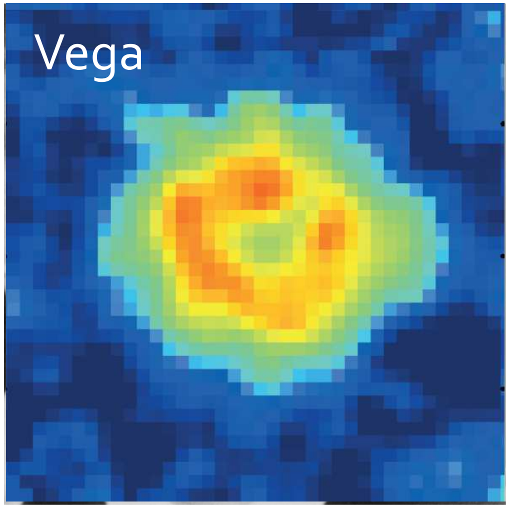


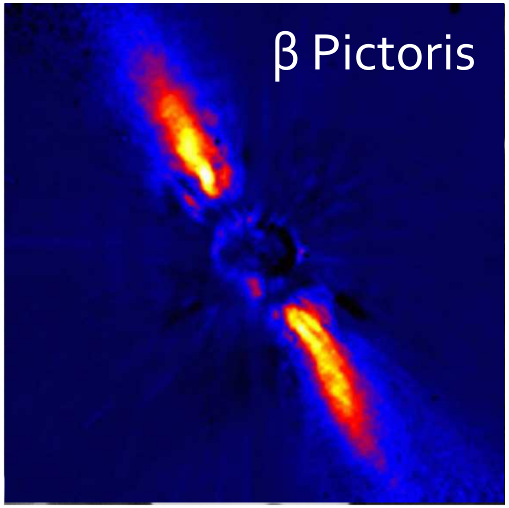
Alternative scenarios

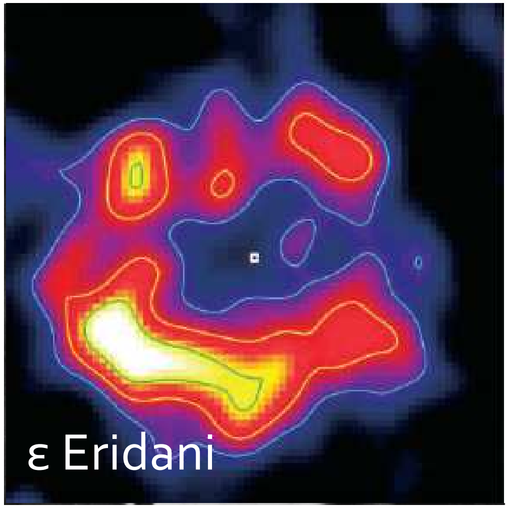
- Misalignment may date back to formation (disk)
- Early stellar encounter (Bate et al. 2010)
  - Stellar cluster → chaotic environment
  - Interactions → misalignment + truncation
- Magnetosphere-disk interactions (Lai et al. 2011)
  - Magnetic protostar exerts warping/precessional torque on inner disk before disruption
  - Disk resists warping → back-reaction torque
- Interaction with gas-rich birth cluster (Thies et al. 2011)
  - Passage of young star through gas reservoir → capture of gas onto existing disk
  - Disk can be tilted up to retrograde

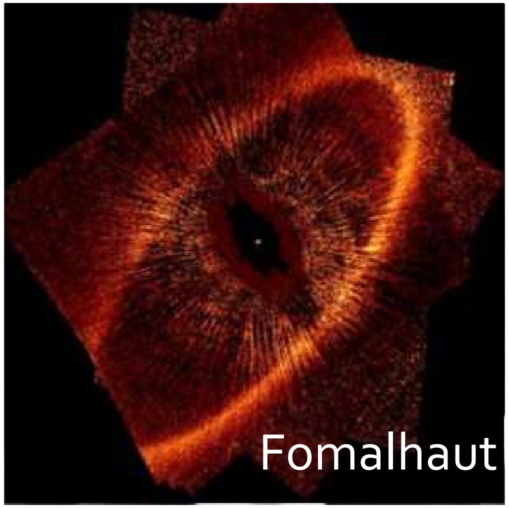
How to discriminate?

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







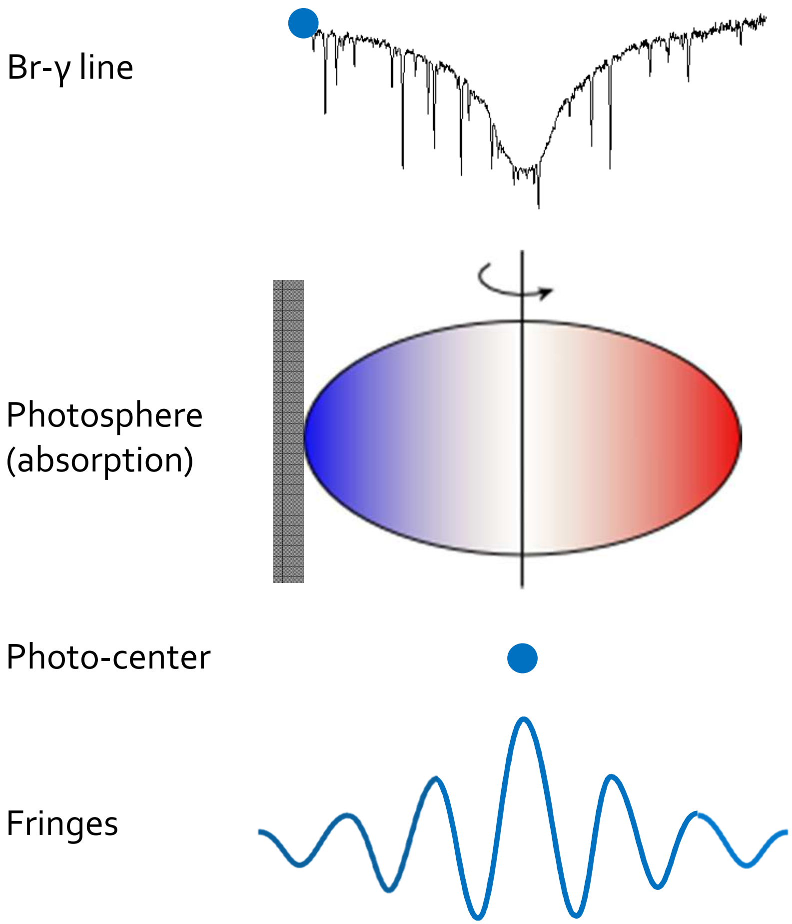


How to get stellar orientation?

- 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°
    - New Herschel resolved disks → 1st misaligned case?
- Position angle from spectro-interferometry
  - Only for rapidly rotating stars (A / early F)
  - Subject of this talk

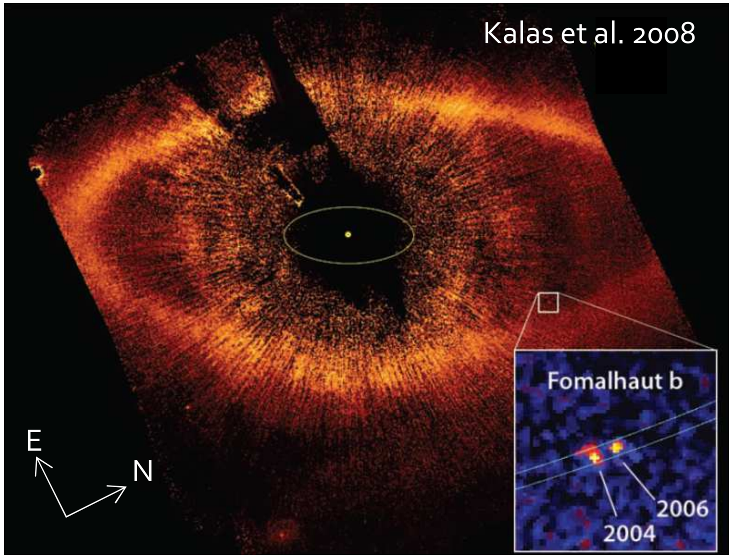
PA from spectro-interferometry

- 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

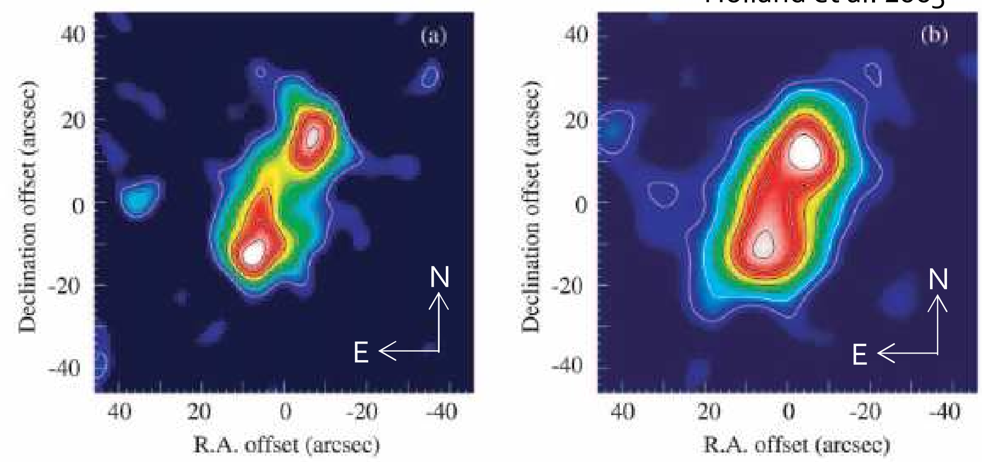


The Fomalhaut planetary system

- Fomalhaut: A4V, 7.7 pc
- Debris disk resolved at various wavelengths
  - Ring at 140 AU
  - Brightness asymmetry
  - Sharp inner edge
  - Off-centered by 15 AU
- Candidate planet at 115 AU
  - Orbital movement



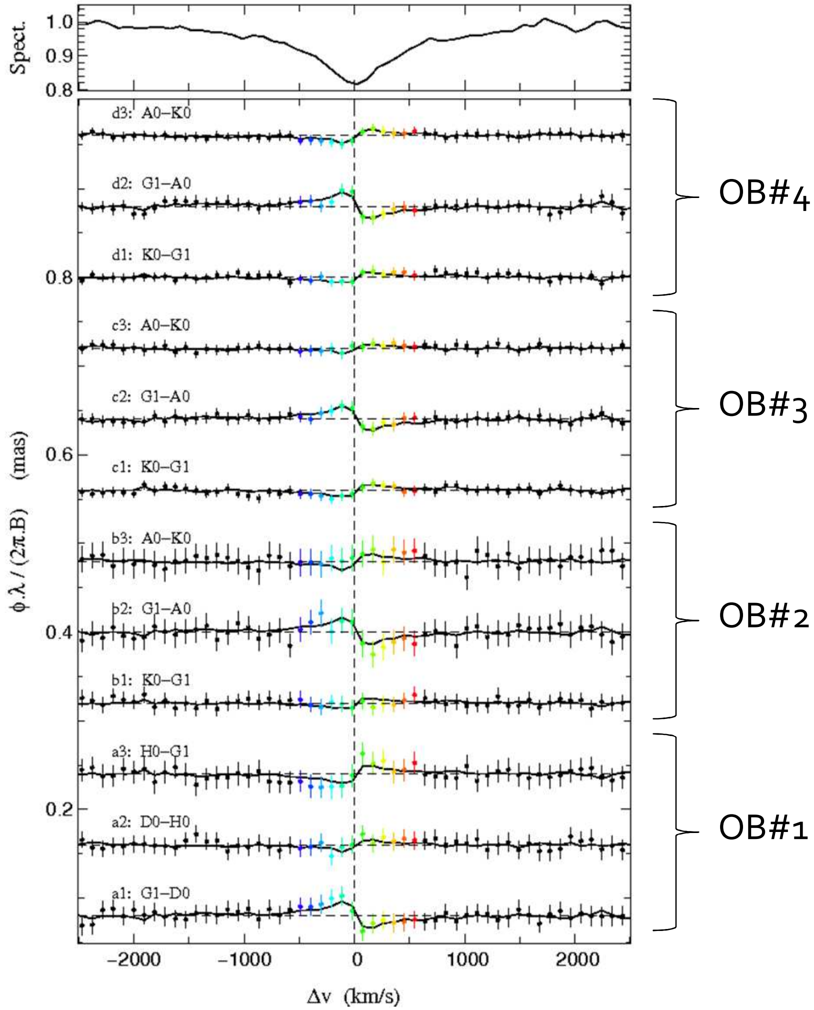
Holland et al. 2003



Fomalhaut with VLTI/AMBER

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

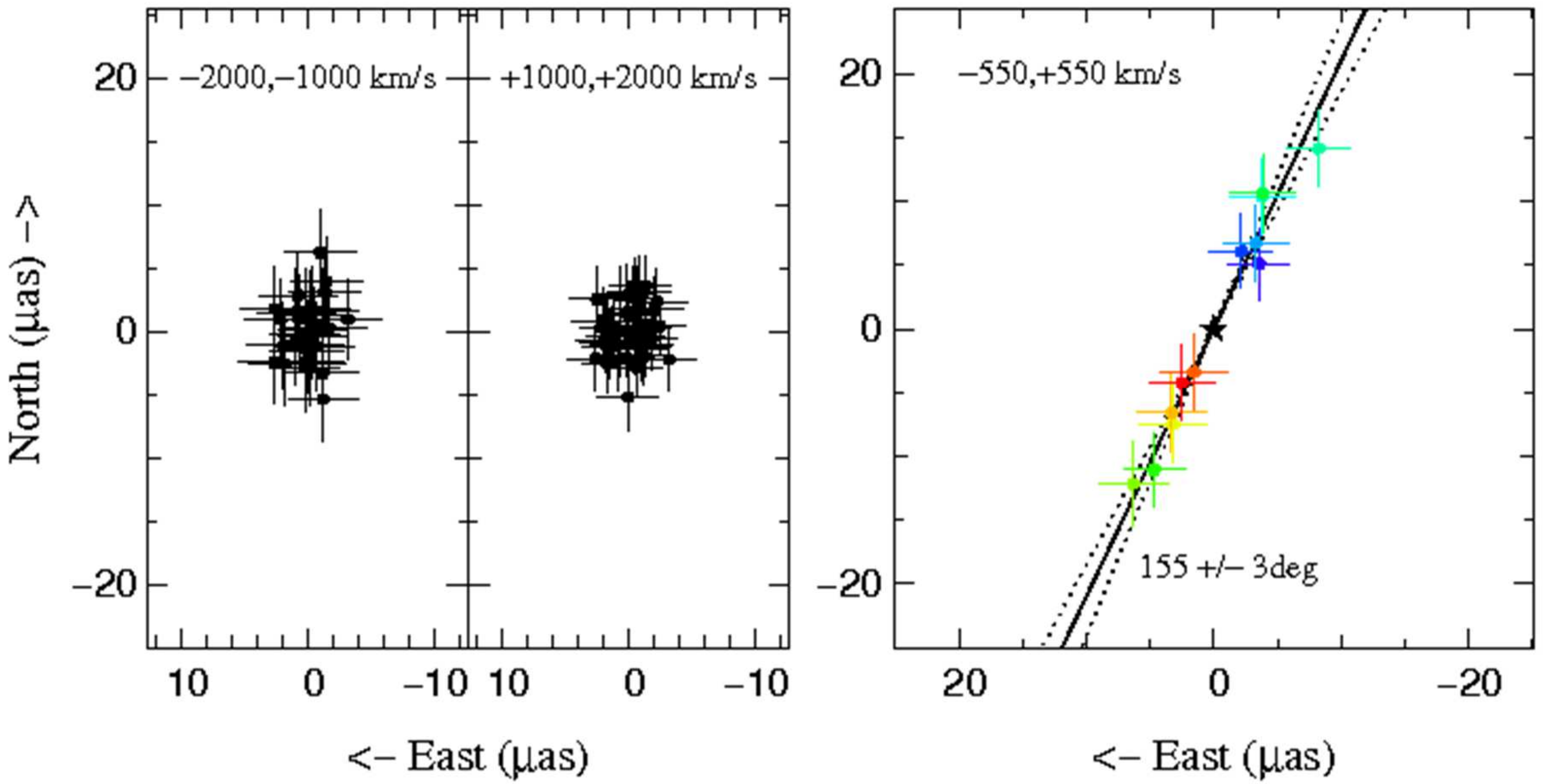
Le Bouquin et al. 2009



2D differential astrometry

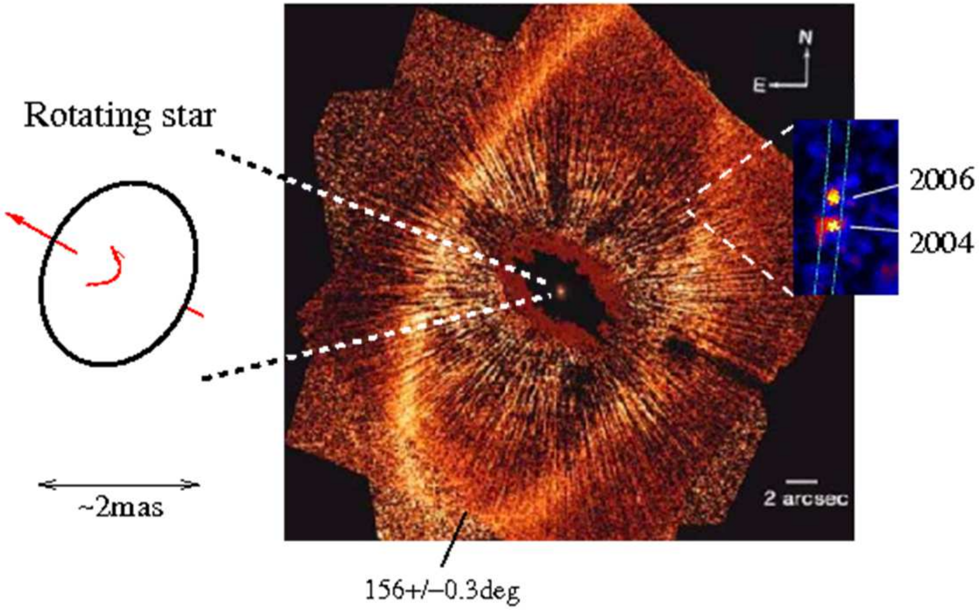
- Clear signature inside Br-γ line
  - Precision: ~3 μas

Le Bouquin et al. 2009



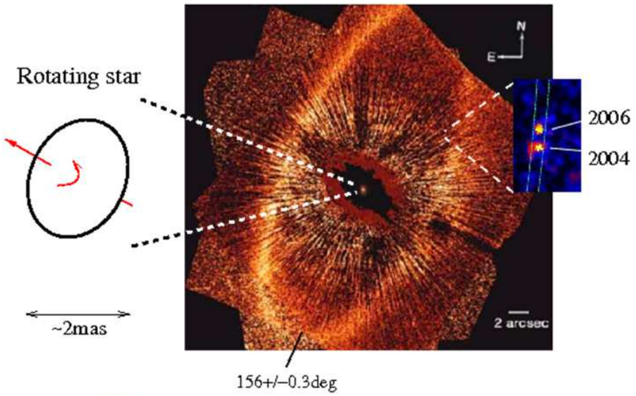
Spin-orbit alignment

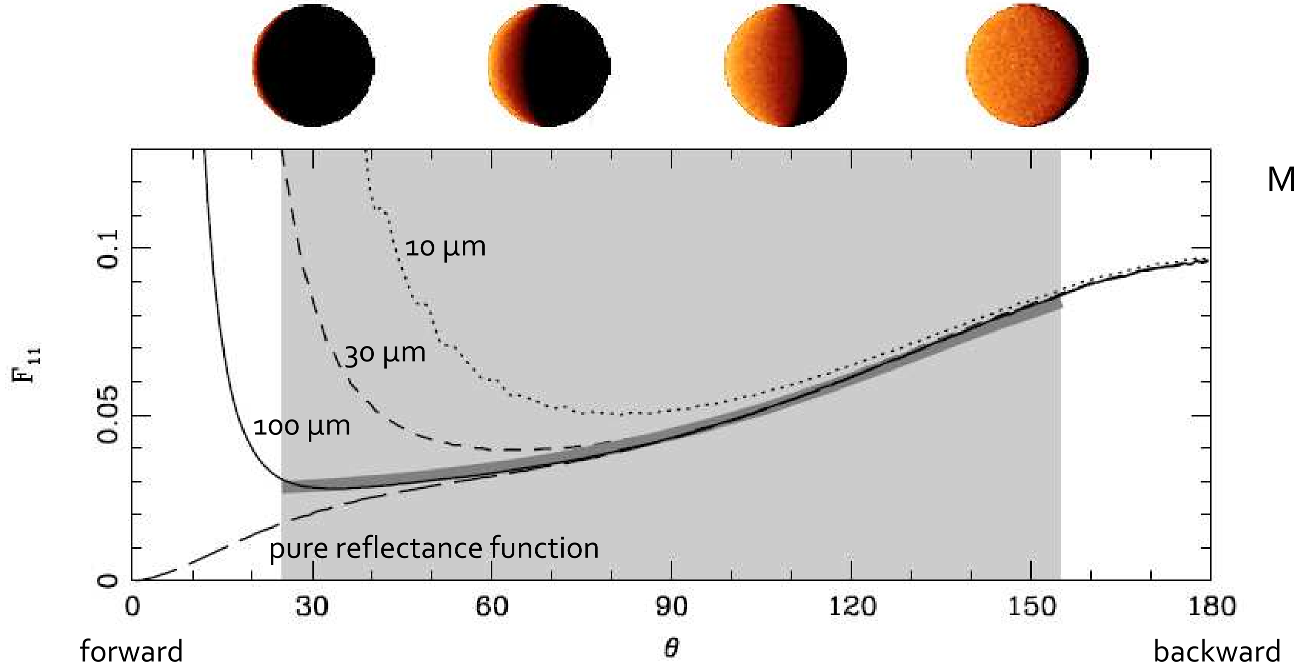
- Photosphere position angle: 155° ± 3°
  - But inclination not constrained (needs advanced model)
- Disk position angle: 156.0° ± 0.3°
- By-product: discriminate front side / back side
  - Assuming planet prograde and stellar spin not flipped



Backward scattering dominant?

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

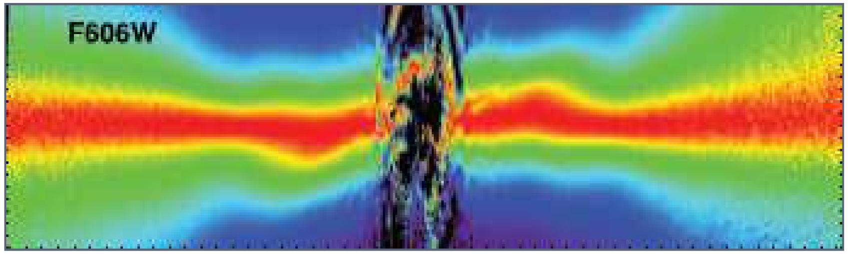


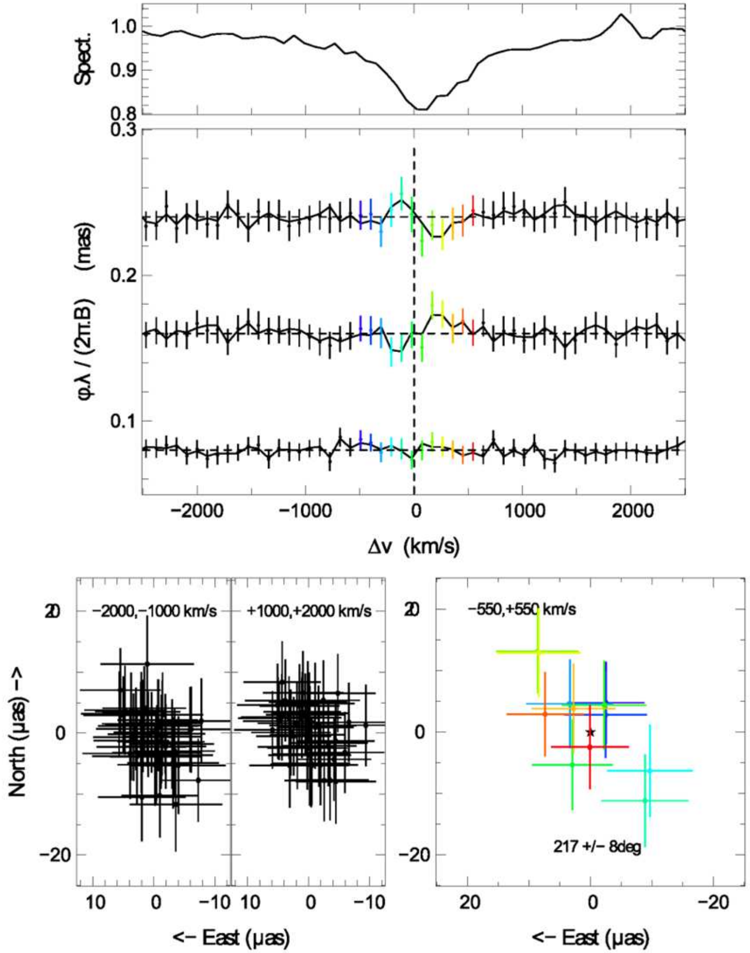


Min et al. 2010

Future work: mini survey

- 6 more potential targets for VLTI/AMBER
  - + a few more to the North
- Zeta Leporis
  - Position angle retrieved while θ = 0.75 mas only
- Beta Pictoris
  - Star aligned with inner or outer disk?





Fomalhaut with VLTI/PIONIER

- Detection limits based on closure phases
  - 7 OBs in total (~3h)
  - 7 spectral channels within K band