Extra-solar planets

Detection techniques and results

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Topics

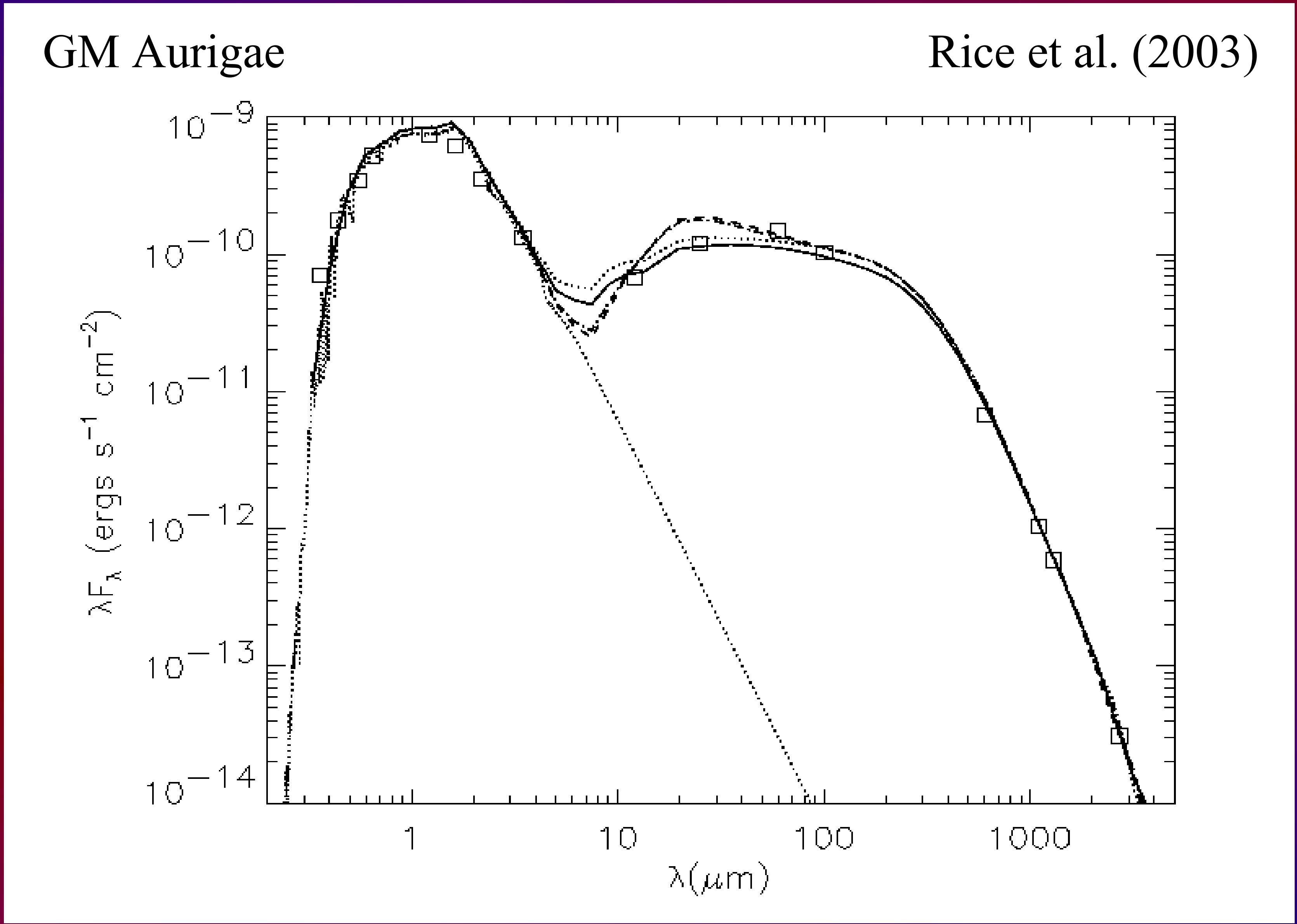
- Day 1:
  - Planet formation: a short introduction
  - Direct detection and astrometry
  - The Radial-velocity technique
- Day 2:
  - Transits
  - (Very) briefly: other planet detection methods
  - Exoplanets: Results and future

Where do planets form: disks

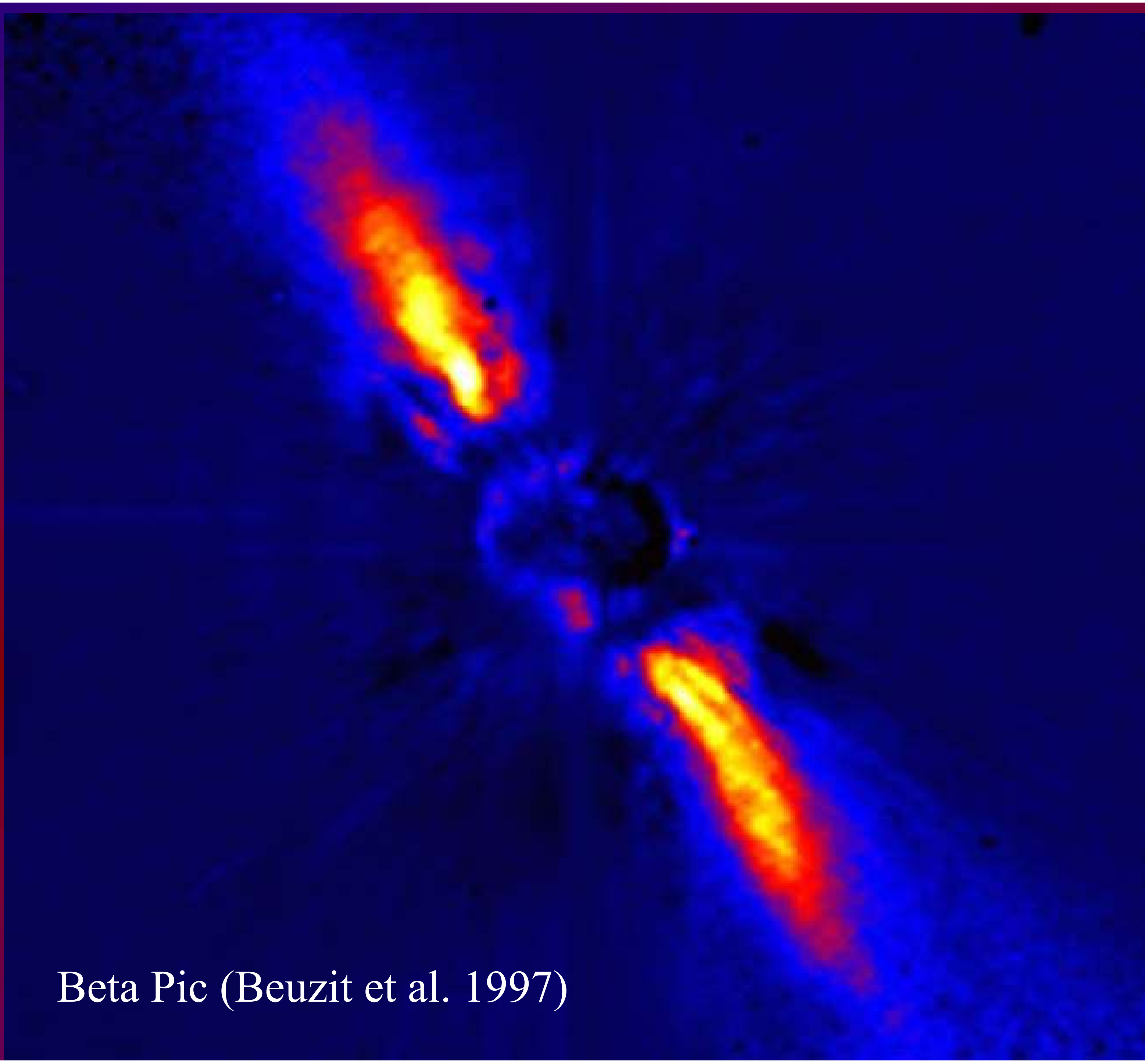
- Radio astronomy (mm-wavelengths)
  - Presence of molecules (CO, NH, ...) + continuum emmision
- Infra-red astronomy
  - Dust continuum emission
- Imaging
  - IR and optical
  - Debris disks and silhouette disks

"Disks" in optical light

Disk presence from IR photometry



Debris disks (remains from proto-planetary disk)



Disk properties (mostly from IR phot)

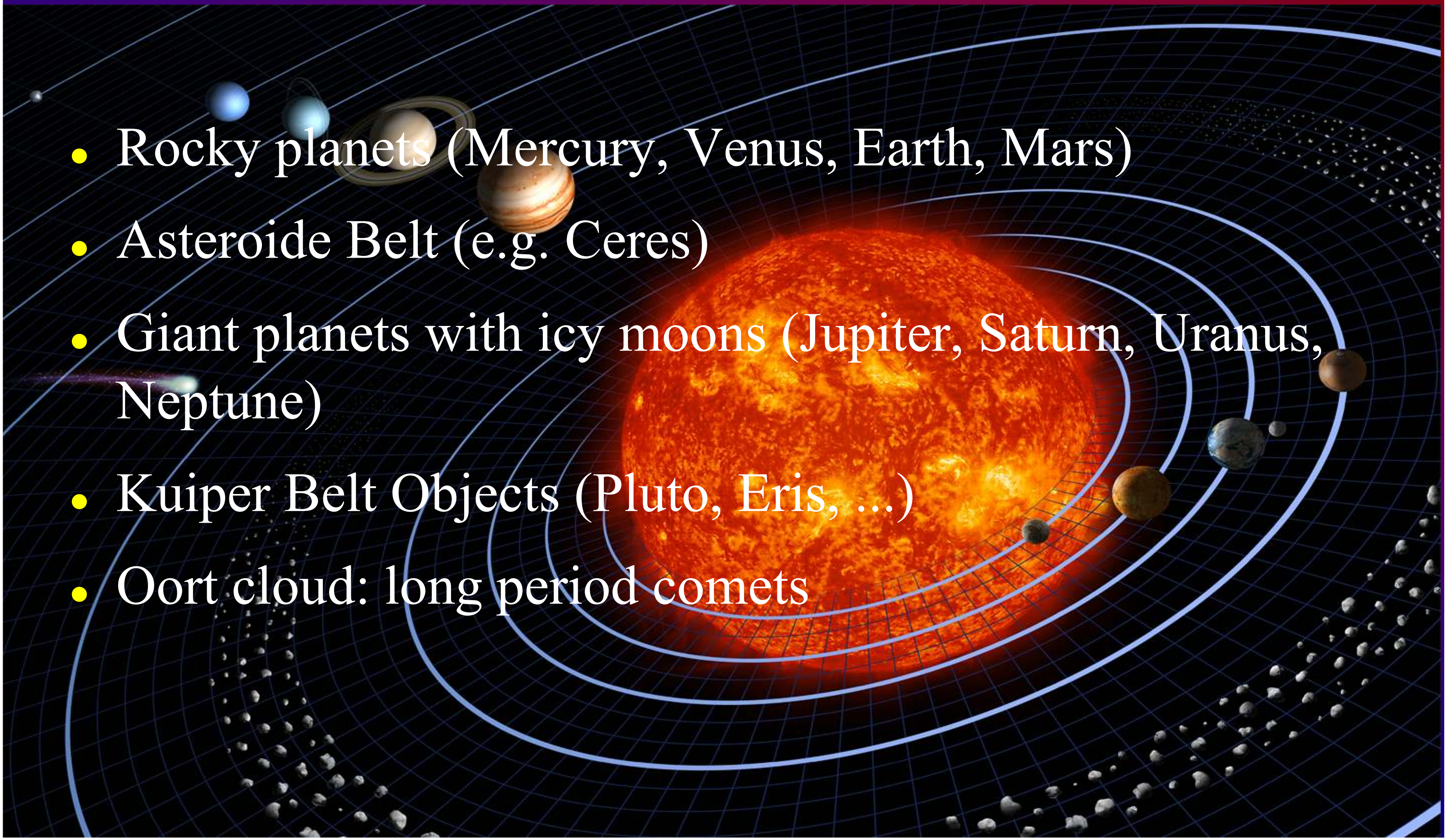
- Masses:
  - 0.001-0.2 M_{sun} (Beckwith 1996) (peek at 0.05)
- Accretion rate:
  - 10^{-8} M_{sun}/year (at 1Myr) (Hartmann et al. 1998)
- Lifetimes:
  - 10^{7} years (Haisch 2001)
- Radius:
  - 50-500 AU (McCaughrean 1996)

From disk to planets

E. Kant (1724-1804):

Solar system formed in a disk around the young Sun

One planetary system: the solar system



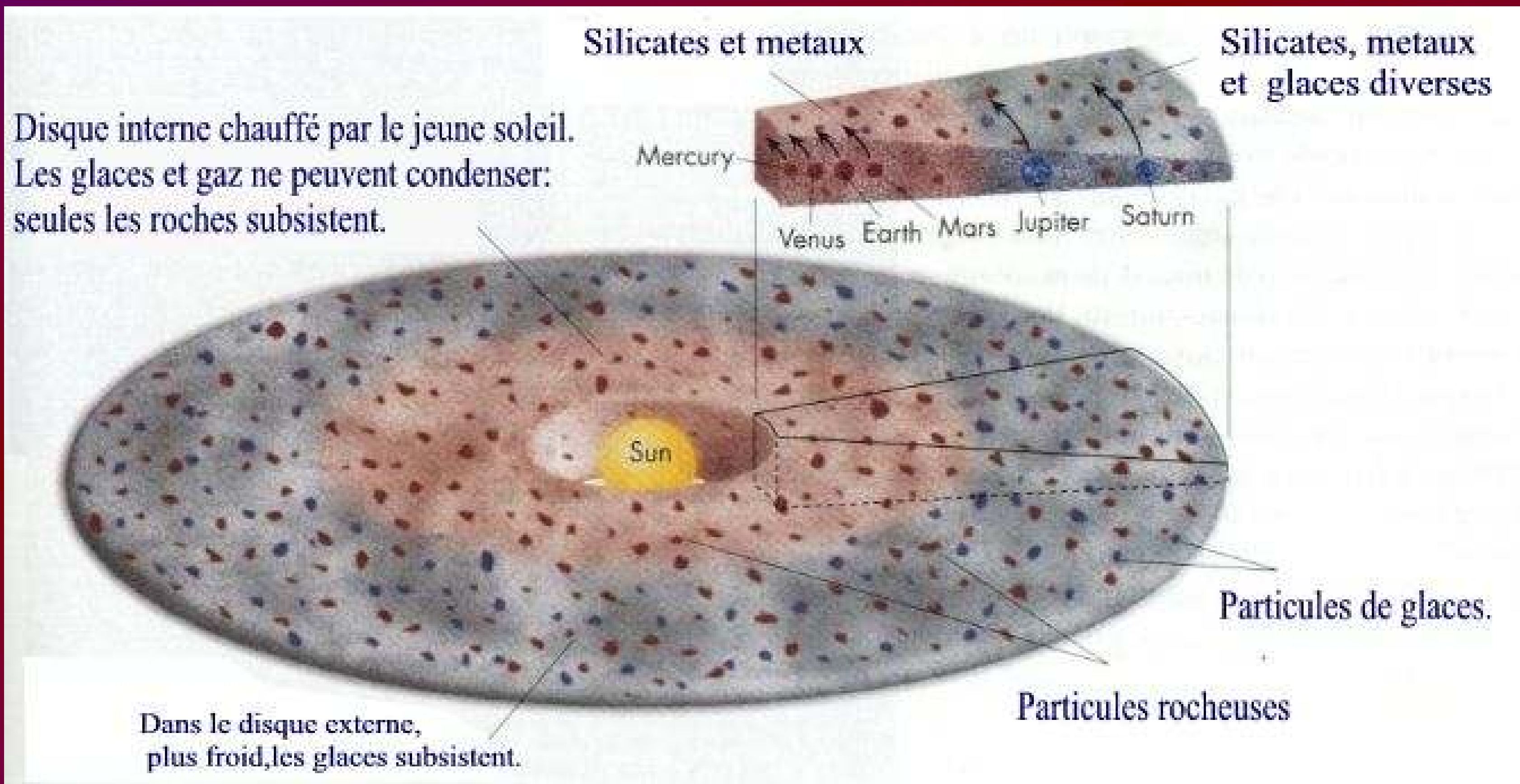
- Rocky planets (Mercury, Venus, Earth, Mars)
- Asteroide Belt (e.g. Ceres)
- Giant planets with icy moons (Jupiter, Saturn, Uranus, Neptune)
- Kuiper Belt Objects (Pluto, Eris, …)
- Oort cloud: long period comets

Basic evidence (dynamics)

- Solar System planets have ~coplanar orbits
- Most planets have ~circular orbits
- Most planets rotate in same direction as orbit
- Most satellites rotate in same direction
- L of planets is much above that of Sun
- Orbital planes are “parallel” to solar-equator
- Asteroid and Kuiper belt objects orbits

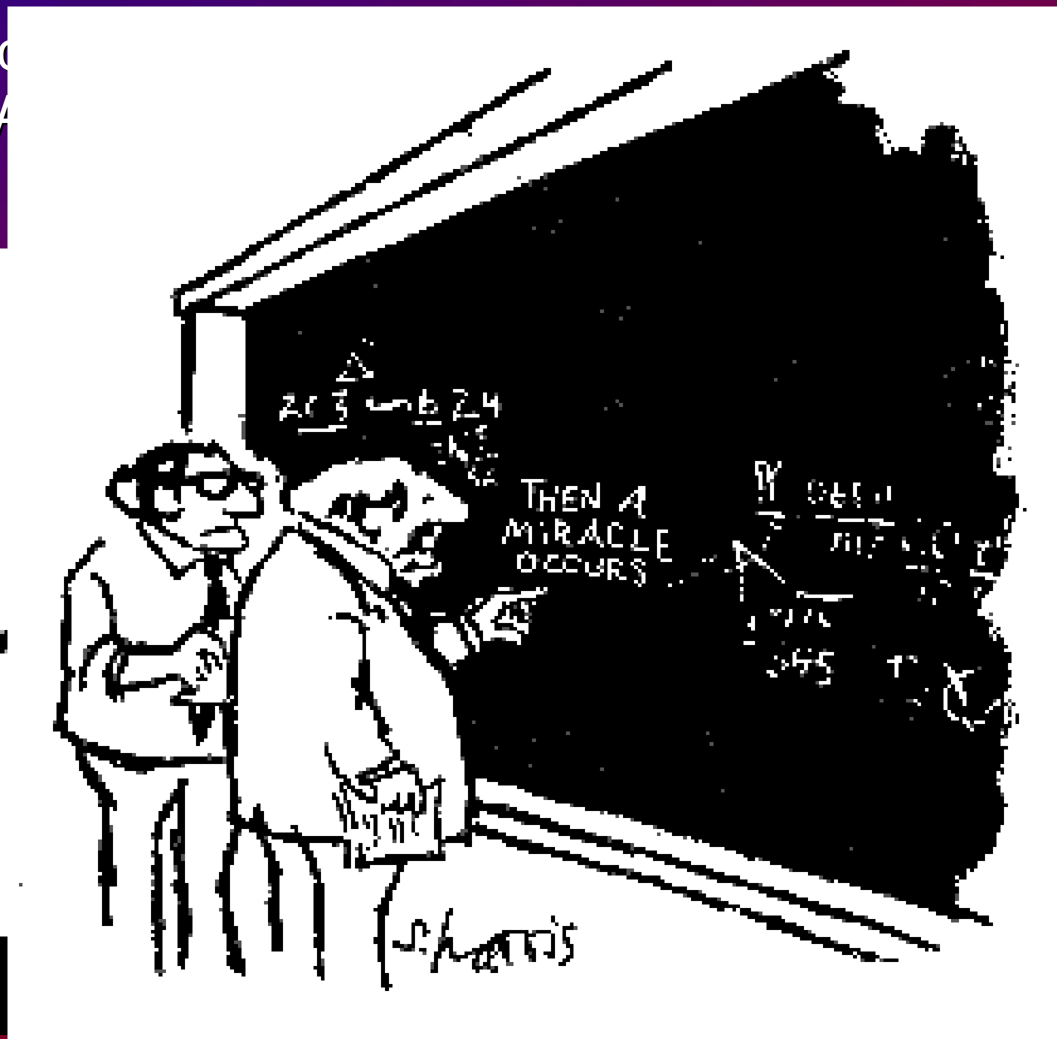
Basic evidence (chemistry)

- Temperature gradient: >3.2 AU ices can condensate
- Explains different density and composition of planets



Rocky planet formation (Safranov 1969)

Inner regi
A



"I think you should be more explicit here in step two."

Dust (mm)

?

↓ Coagulation

Planetesimals (~km)

↓ Collisions

Embryos (~Moon size)

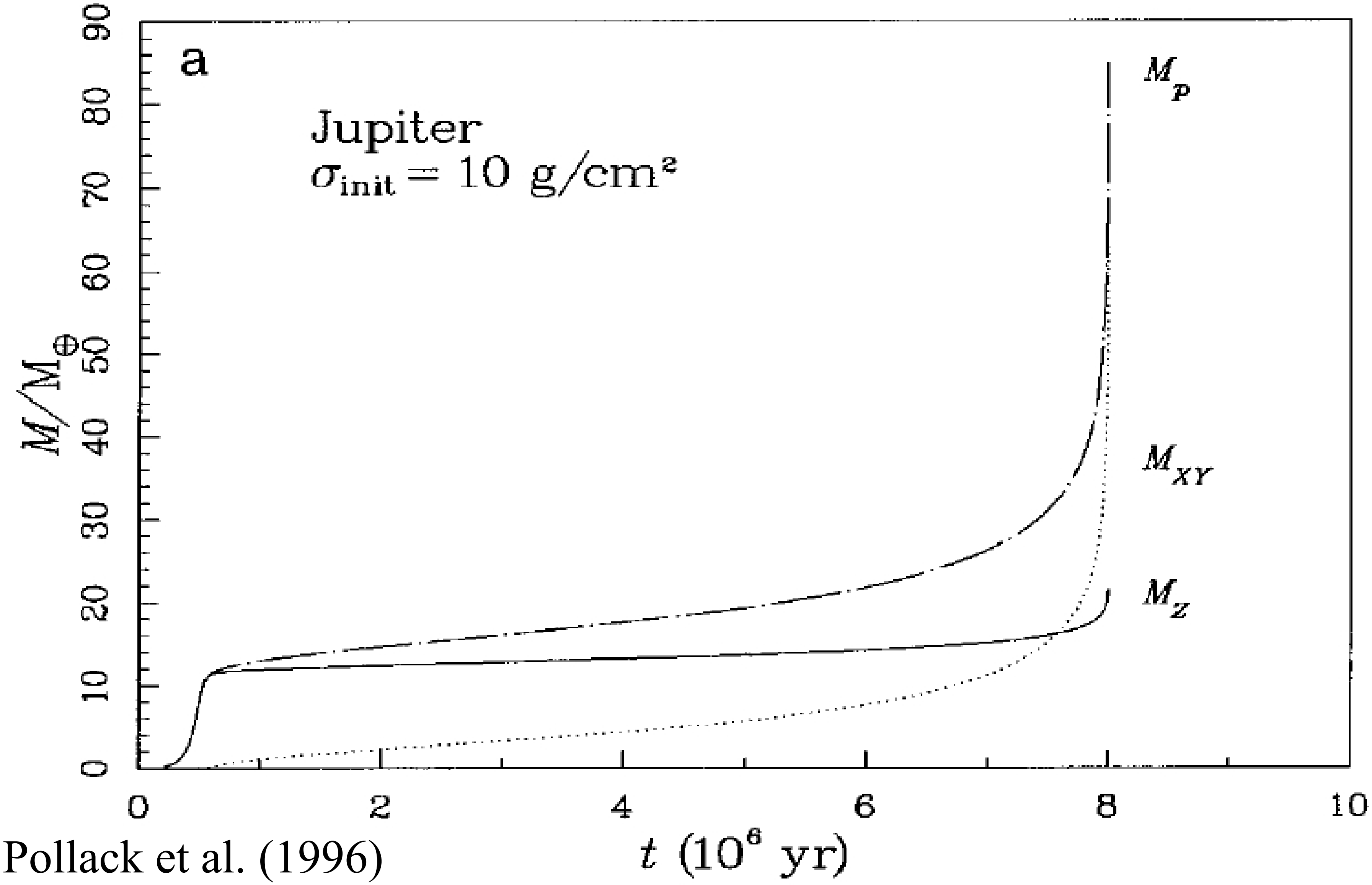
↓ Major impacts

Planets

How do giant planets form?

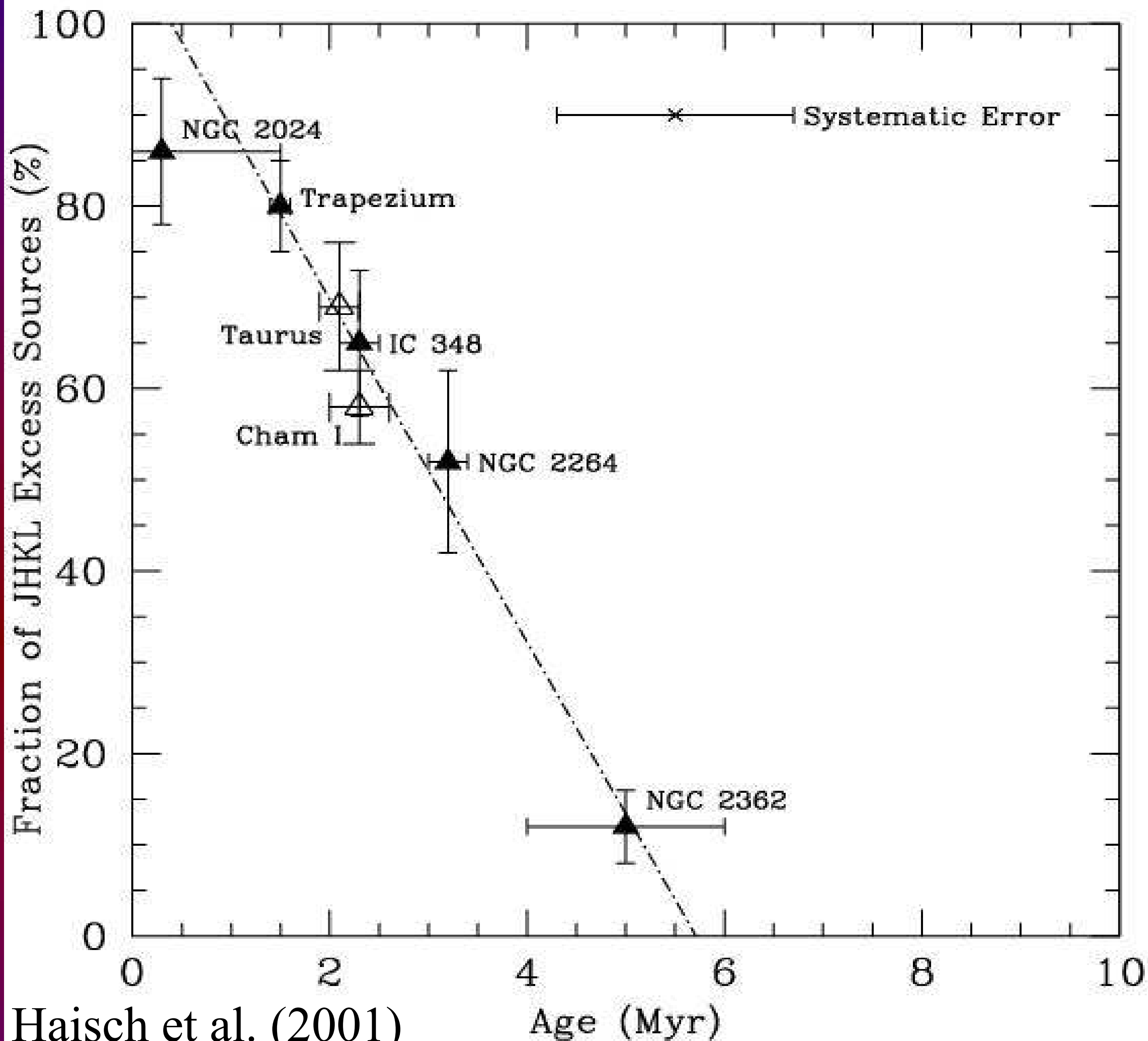
- Giant planets form by core-accretion
  (e.g. Mizuno 1980; Pollack et al. 1996)
- Two step process:
  - Solid (icy) nucleus with 10-20 Earth mass
  - Only possible to form far from the star (~3.2AU)
- Accreted gas around to form giant planet (e.g. Jupiter)
- Uranus and Neptune take longer then Jupiter

Problem with timescale?



Pollack et al. (1996)

Disk lifetimes from IR photometry



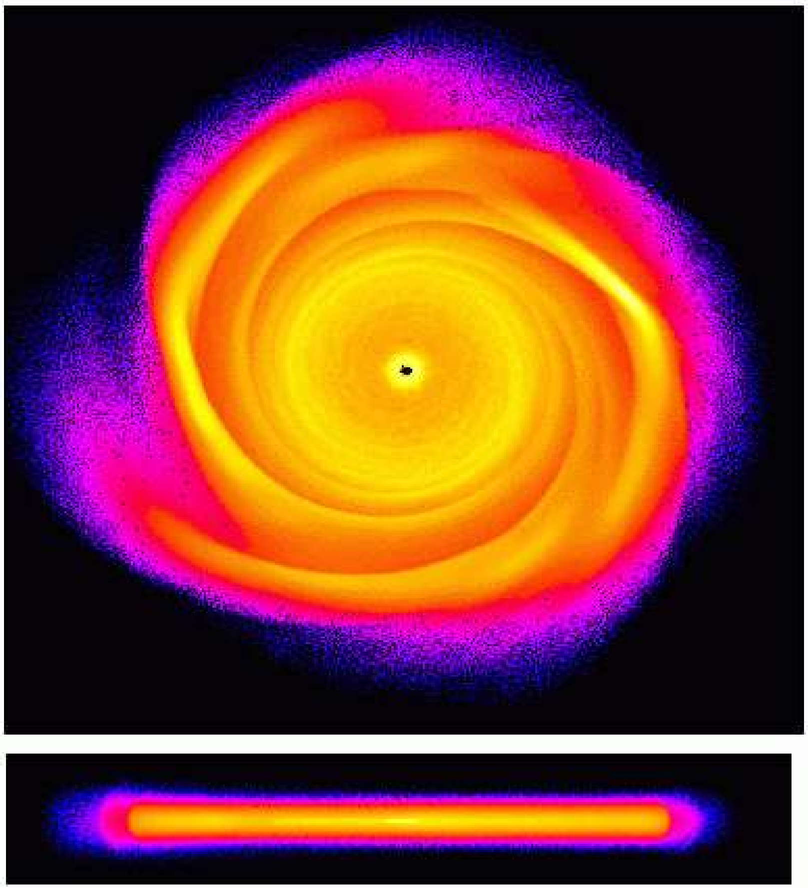
Haisch et al. (2001)

Do we need another model?

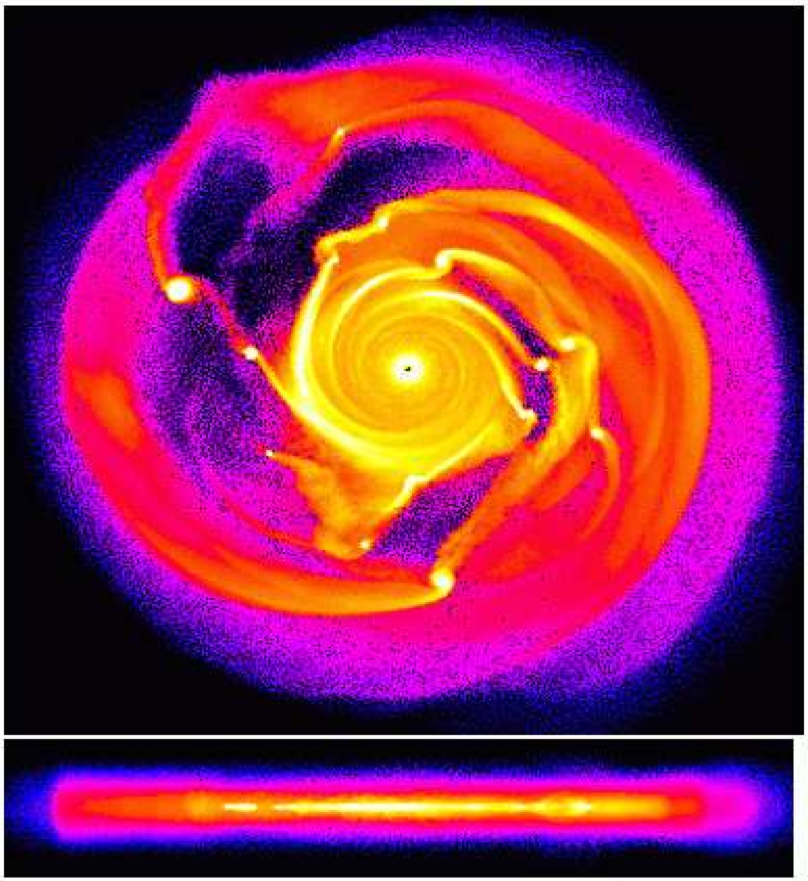
- Disk instability models:
- Planet formed from a gravitational instability in the disk (Boss 1997; Mayer 2000)
- Advantage: formation is very fast
- Disadvantage: not clear if embryos survive

Disk Evolution, Qmin ~ 1.4

1 million particles, locally isothermal eq.of state, R=20 AU



T=160 yr



T=350 yr

Mayer et al. 2000

Is there really a problem?

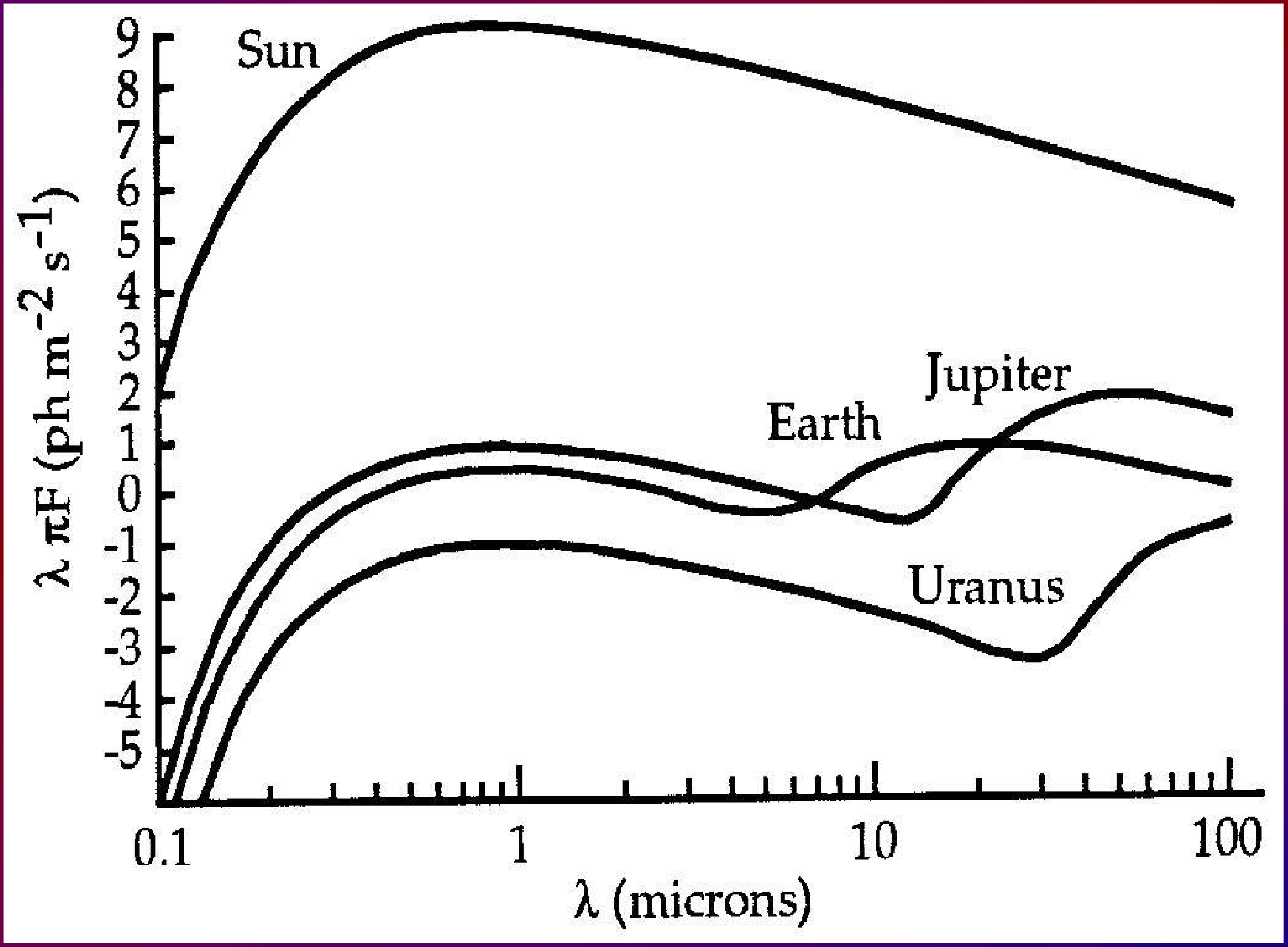
- Maybe disks can last longer than previously though (Bary et al. 2003 – H2 detection)
- Can we accelerate core accretion model?
- Yes! Including planet migration, disk evolution and/or random motion (Alibert et al. 2004; Rice et al. 2003)
  - Giant Planets formed after ~1 Myr

How to find a planet?

- Direct imaging
- Indirect methods:
  - Astrometry
  - Radial-velocities
  - Gravitational microlensing
  - Photometry

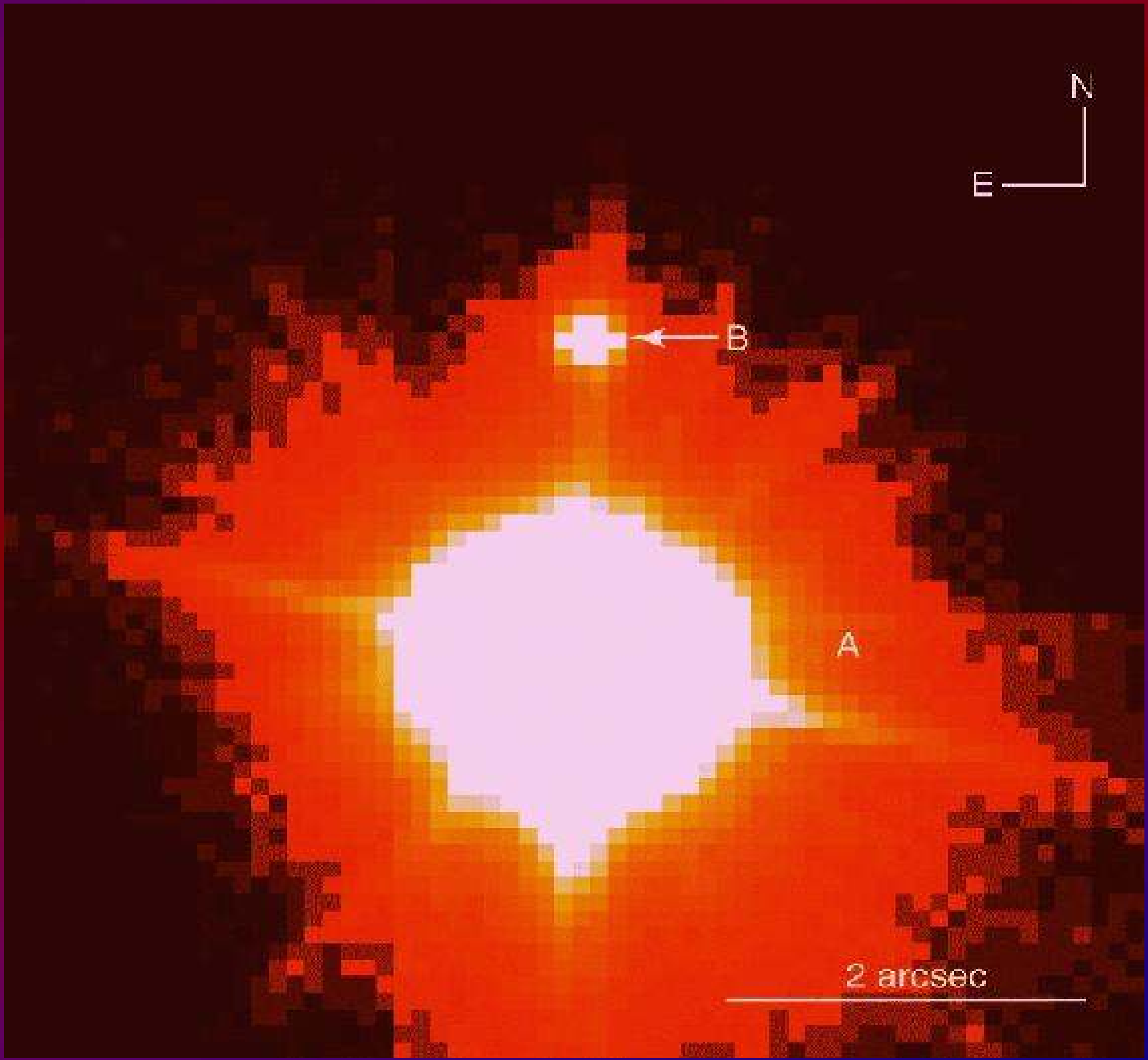
Direct Imaging

- Optical: star is 10^6 - 10^9 times brighter than planet!



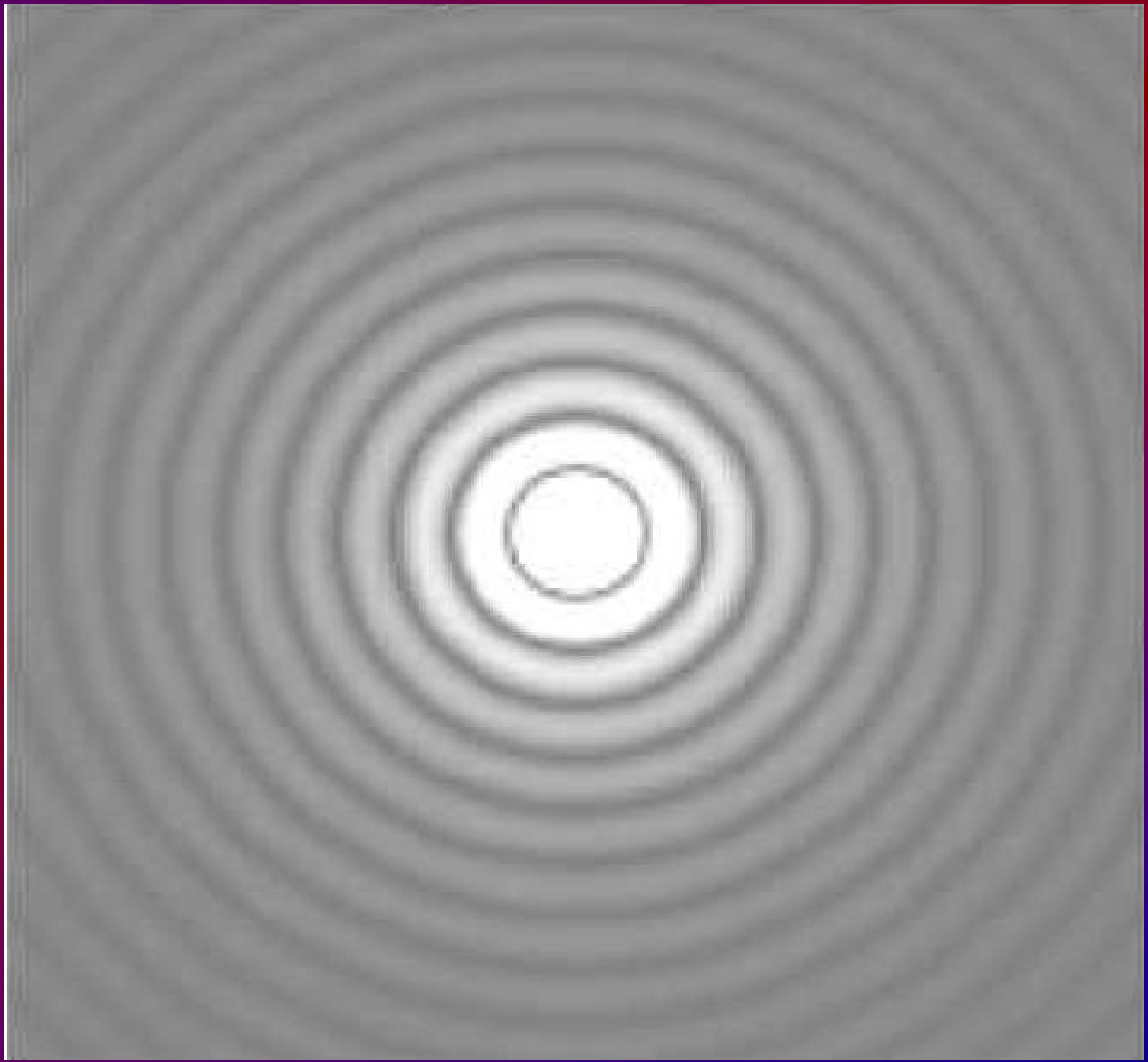
Direct Imaging

- Small separation between star and planet (Sun_Jup: 0.5 mas @ 10pc)
- Planet "lost" in stellar PSF
- Optical: star is $\sim 10^6$ times brighter than planet!



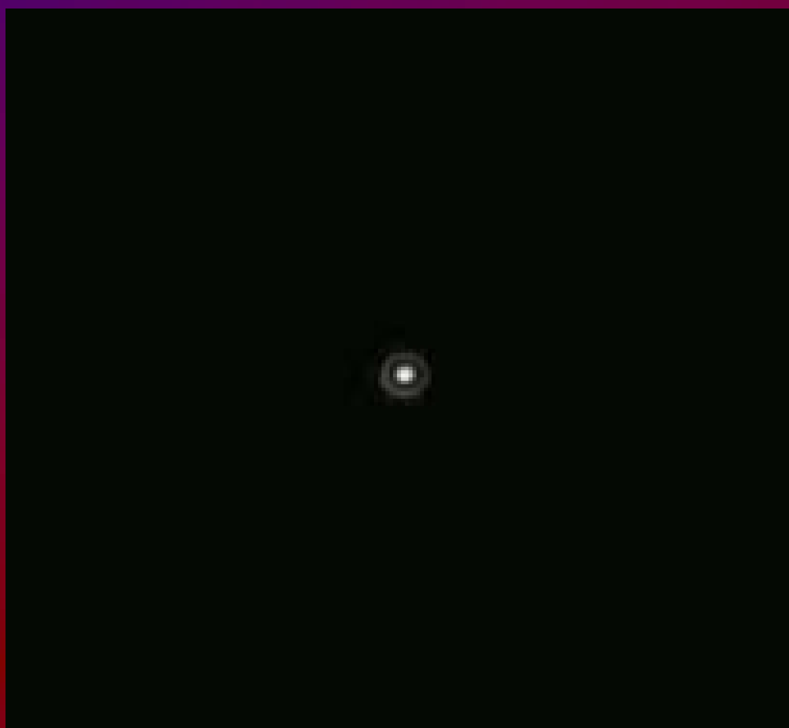
Airy pattern

- The image of a star through circular aperture telescope

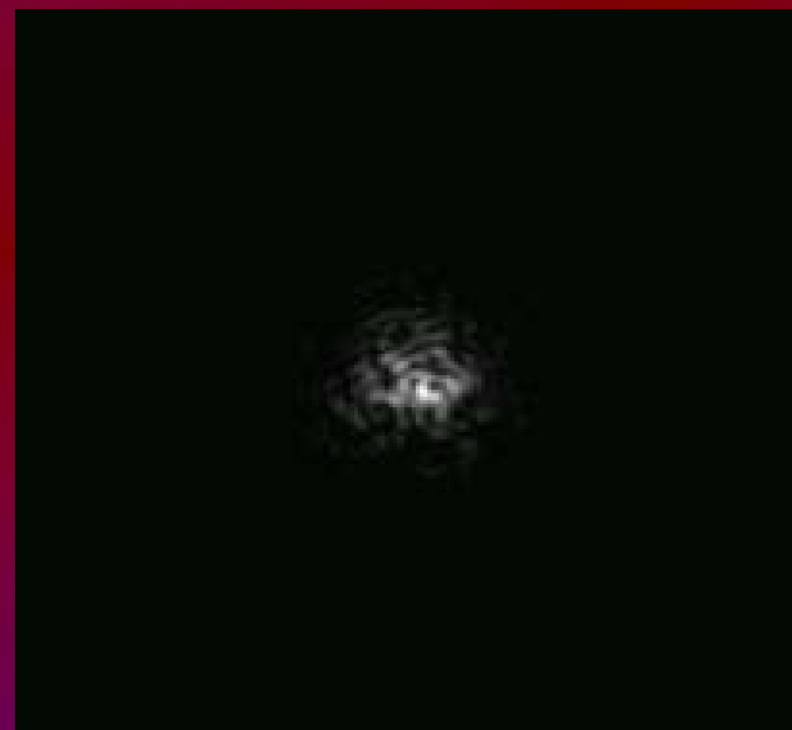


Atmosperic turbulence (seeing)

Good seeing conditions



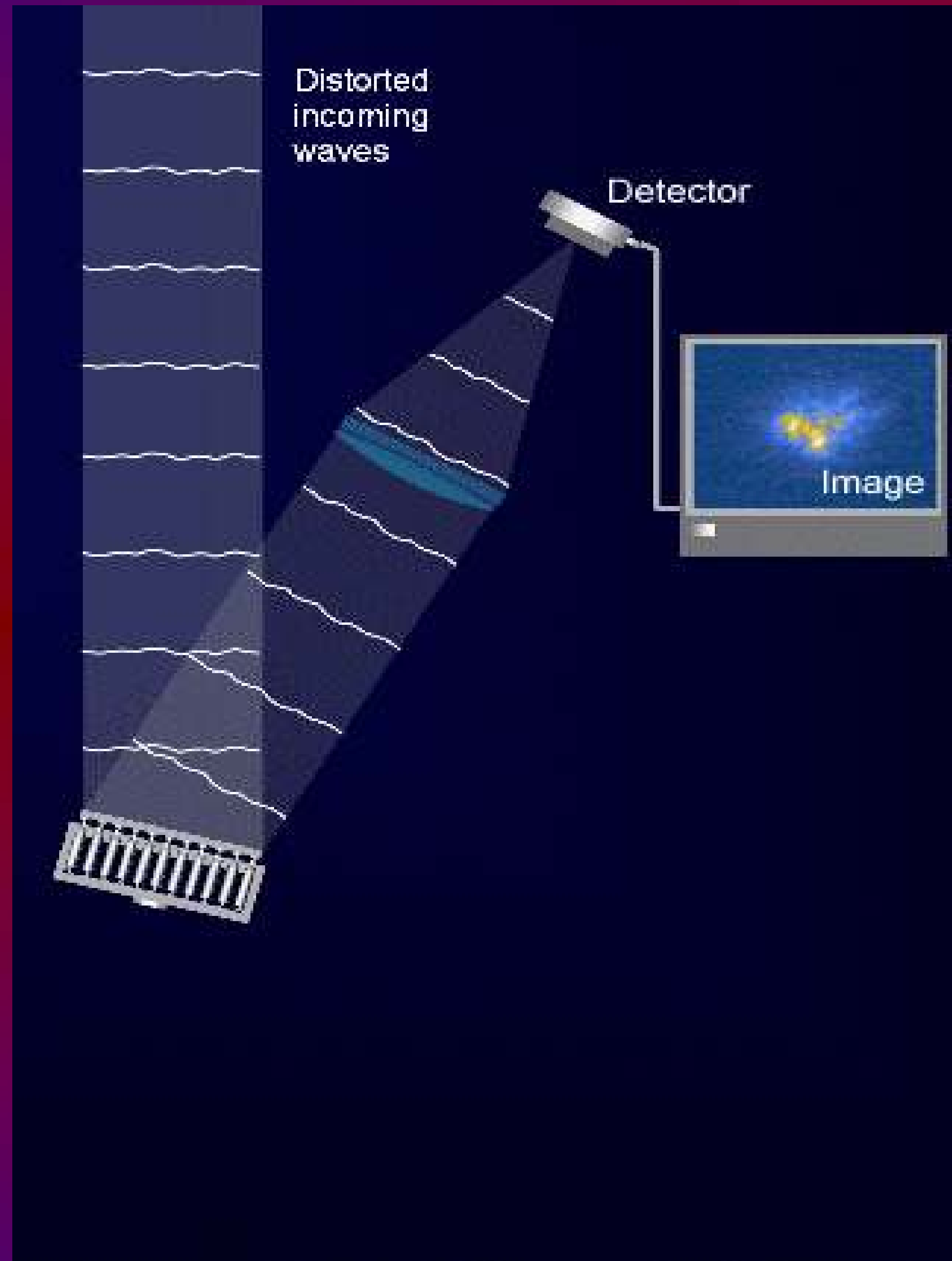
Bad seeing conditions

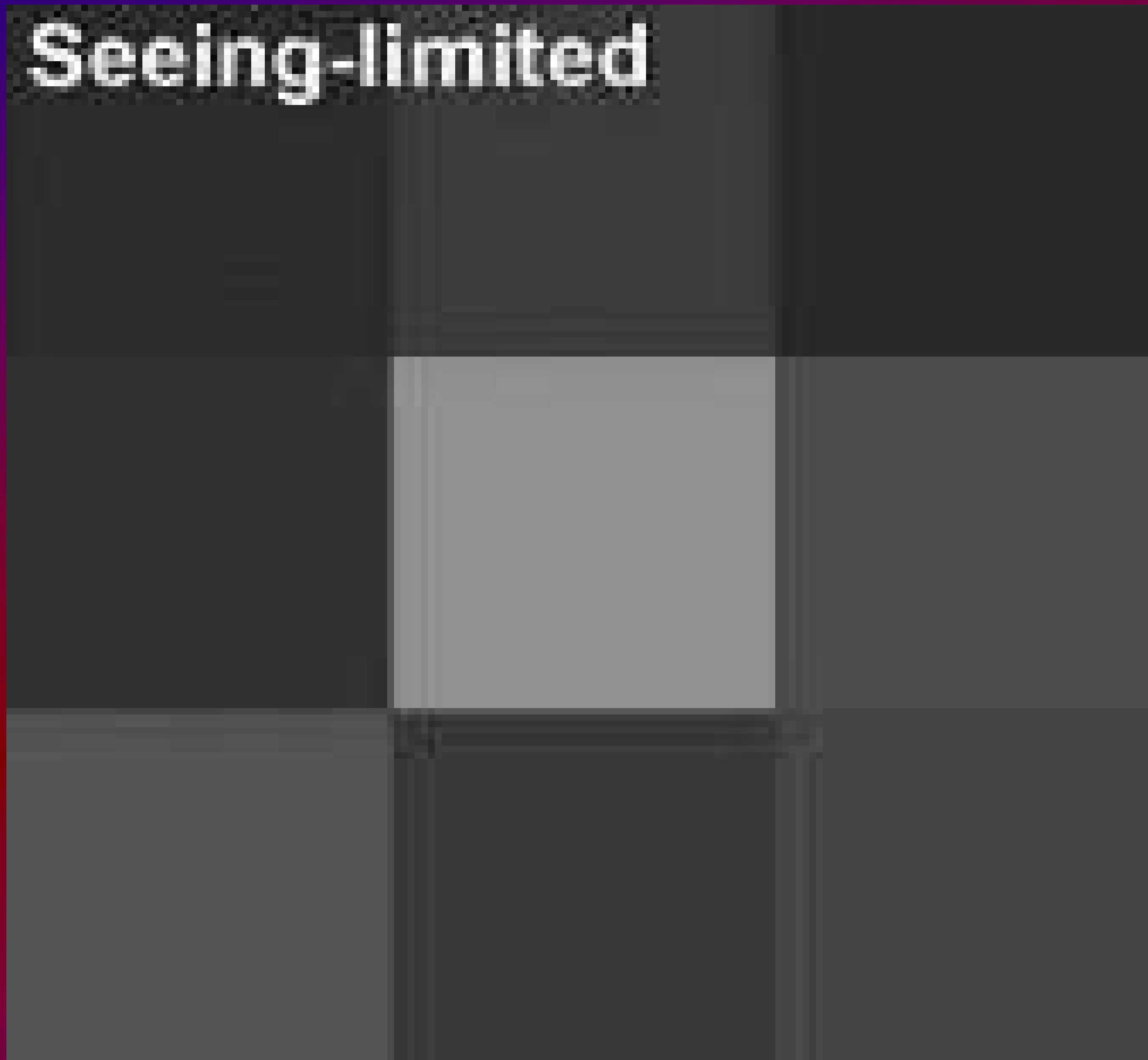


The principle of Adaptive optics

Correct the wavefront to obtain difraction limited images

R=1.22 λ/D

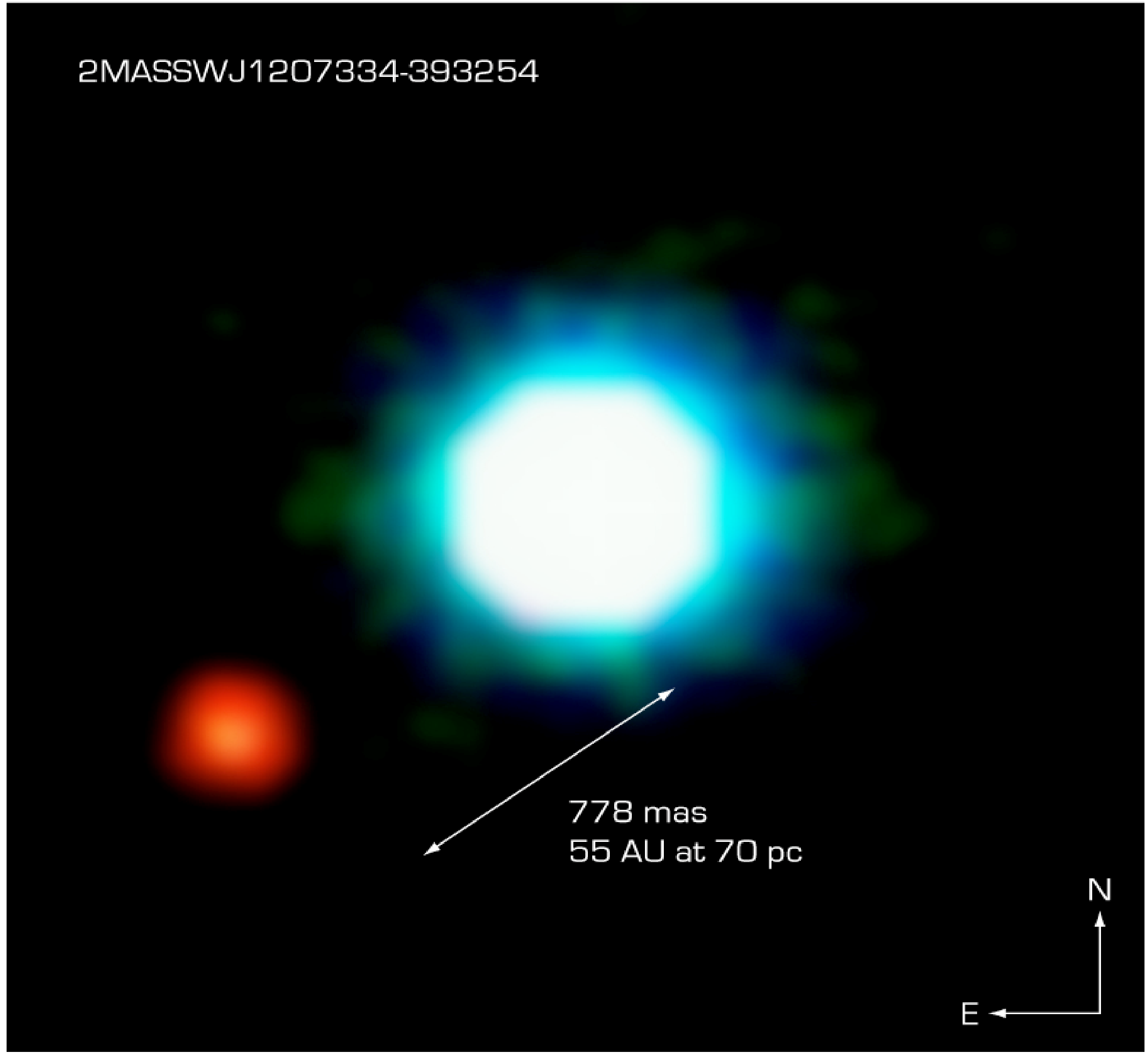



Seeing-limited

First image of exoplanet?

$M=5M_{Jup}$
sep=55UA

Chauvin et al. (2004)

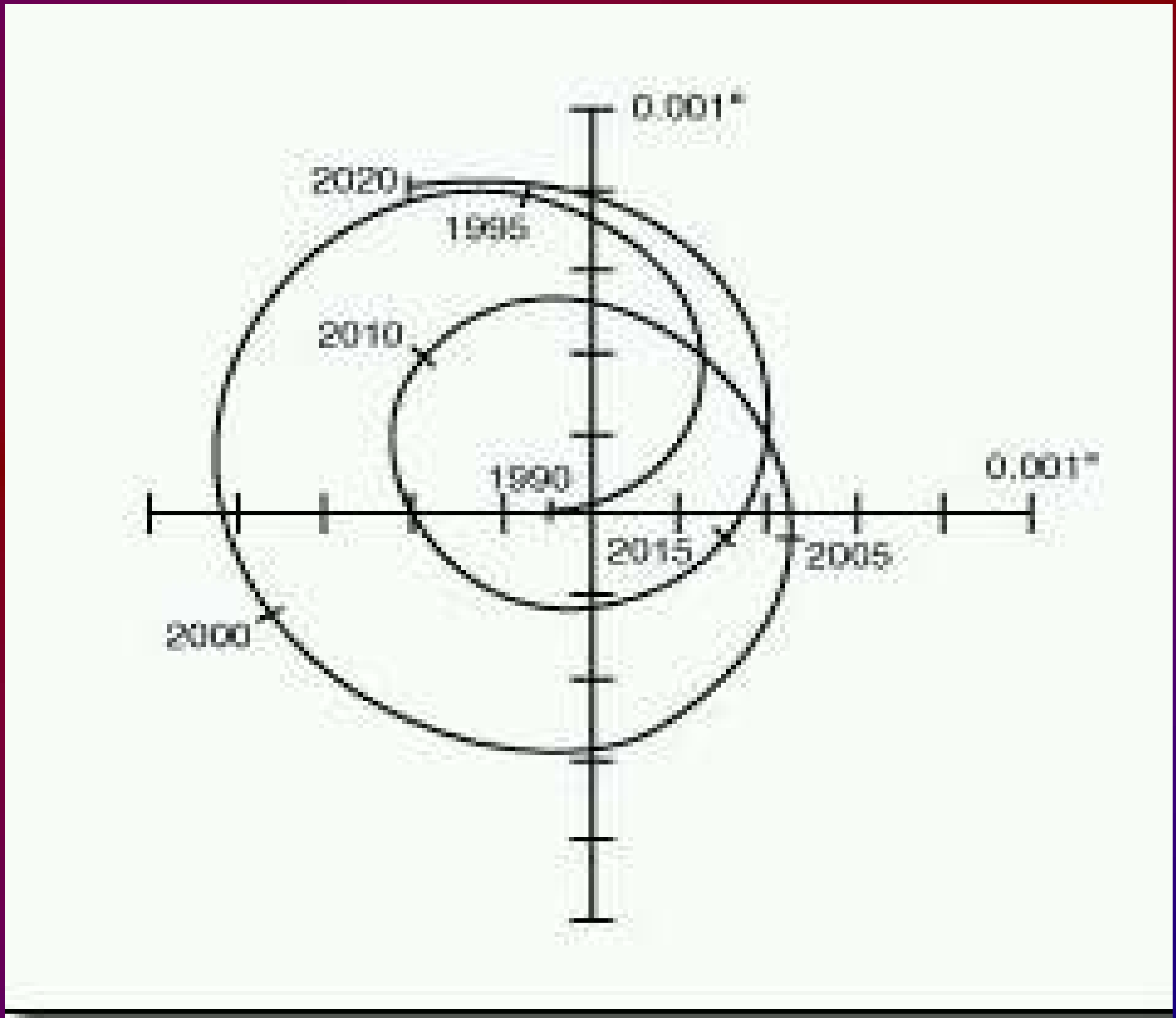


NACO Image of the Brown Dwarf Object 2M1207 and GPCC

ESO PR Photo 26a/04 (10 September 2004)

Astrometry

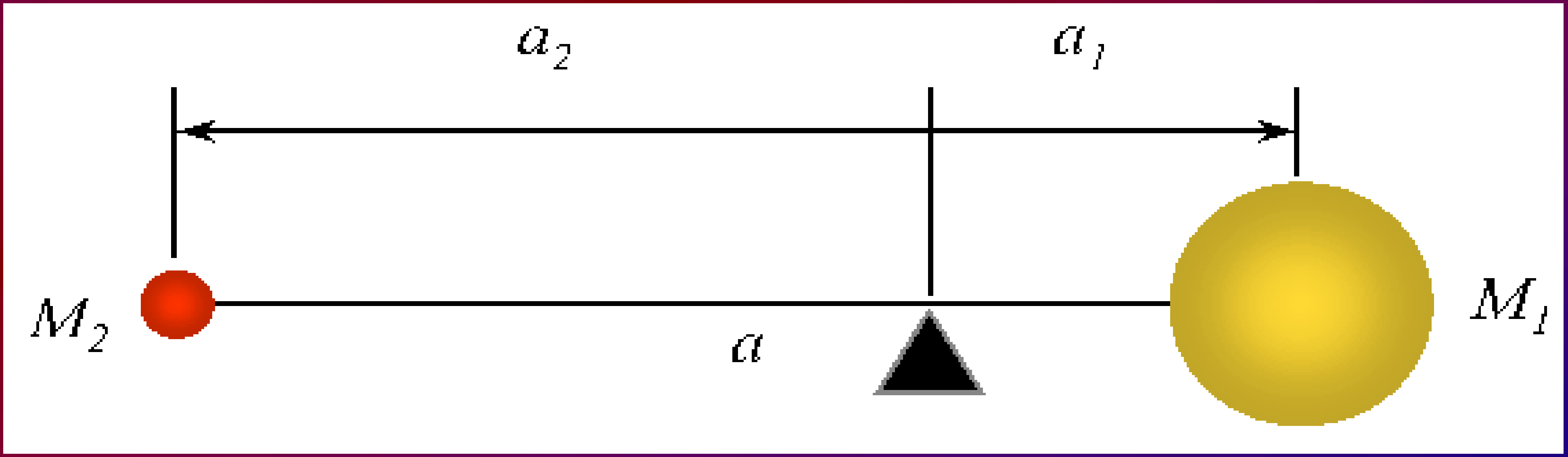
Try to measure the projected orbital motion of the star in the sky



Astrometry

$M_1 a_1 = M_2 a_2$ with $a_1 + a_2 = a$

$P^2 = a^3 (4\pi^2) / G(M_1 + M_2)$ (Kepler 3rd law)



Astrometry

- Problems:

- Small angular displacement: needs very high accuracy
- For planets we only observe a_1
    - Have to derive M_1 from other method (or RV)
- More sensitive to long period planets

Extrasolar planets and Astrometry

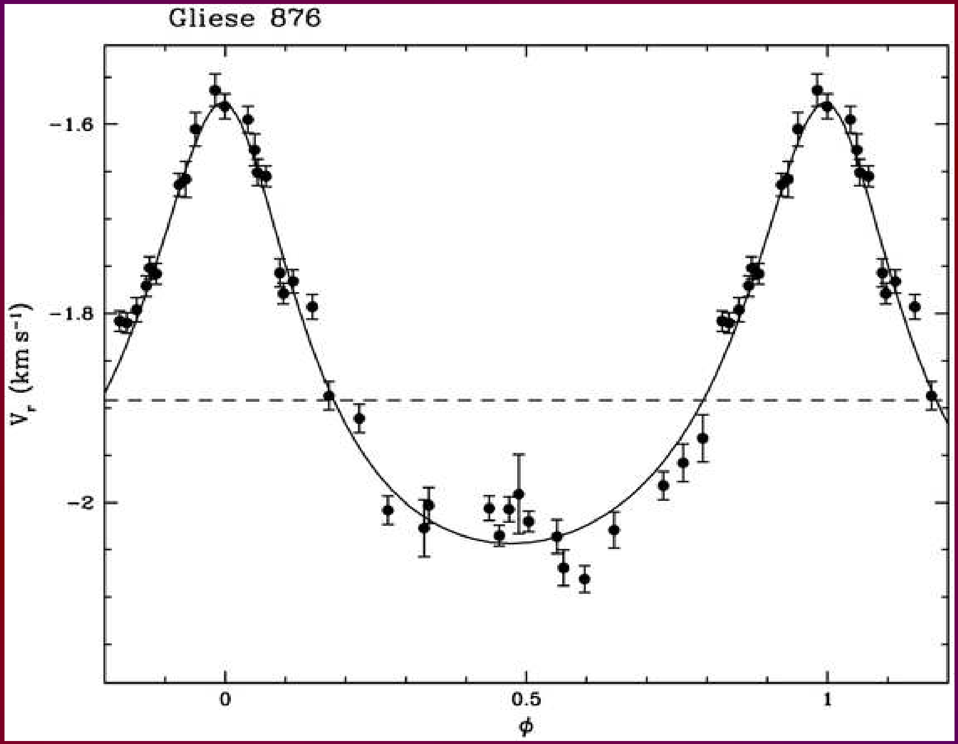
Gl 876

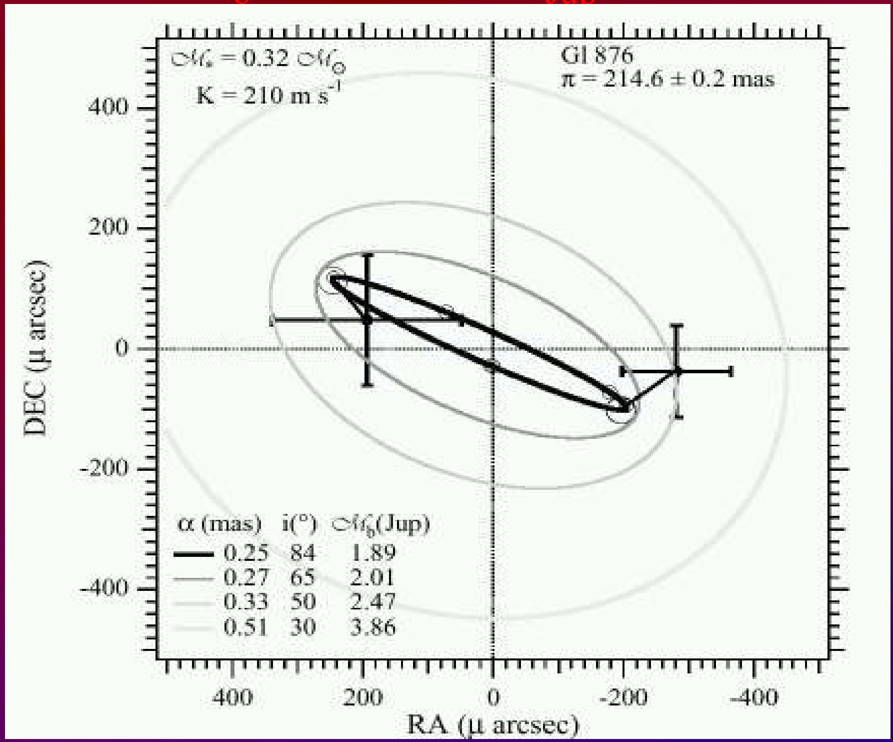
Marcy et al. 1998
Delfosse et al. 1998

CORALIE/KECK

P=61d, K1=210m/s, *e*=0.1

- HST/FGS
- α = 250± 60 μarcsec
- $i = 84^o \pm 6^o$
- $M_b = 1.9 \pm 0.5\ M_{Jup}$



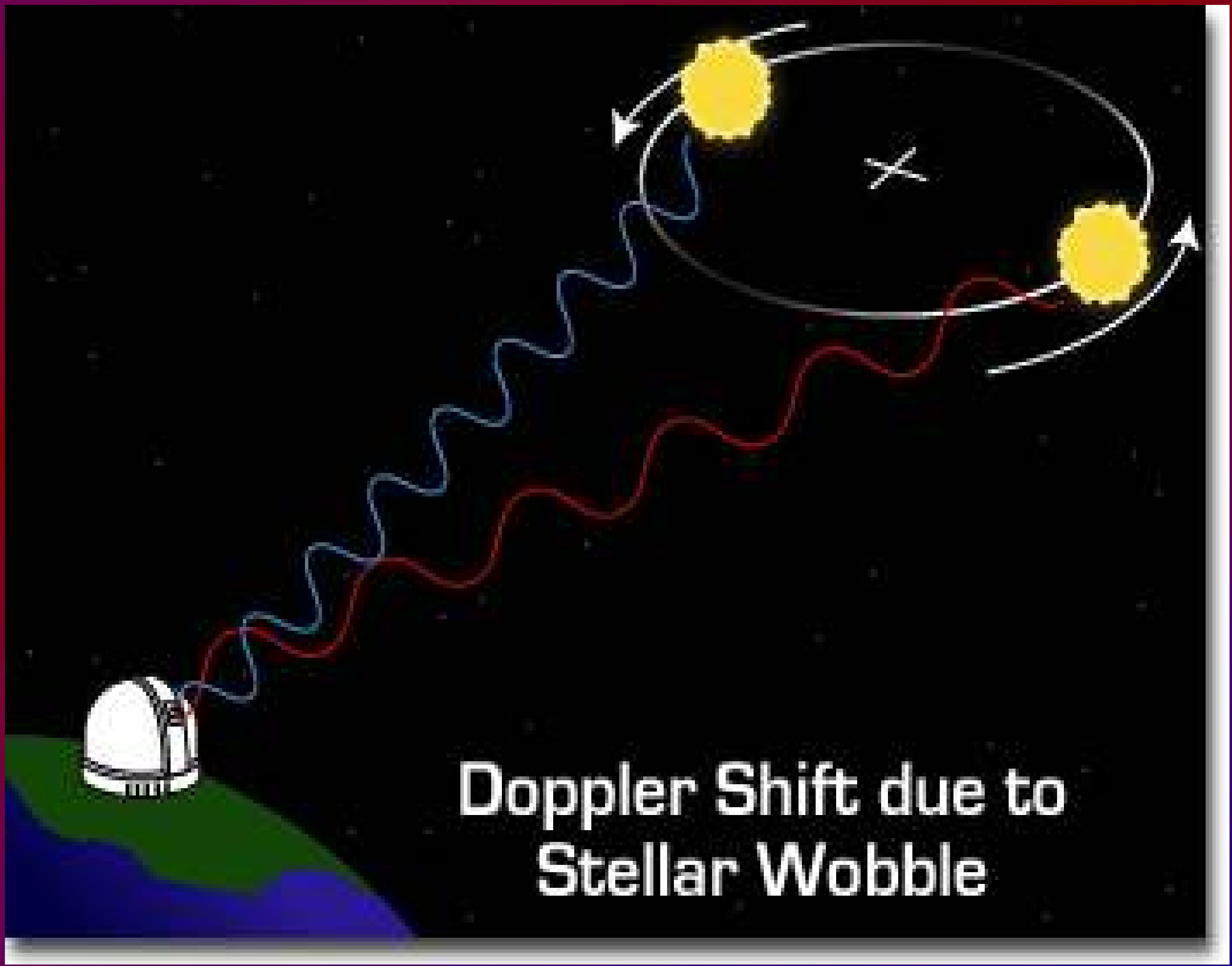


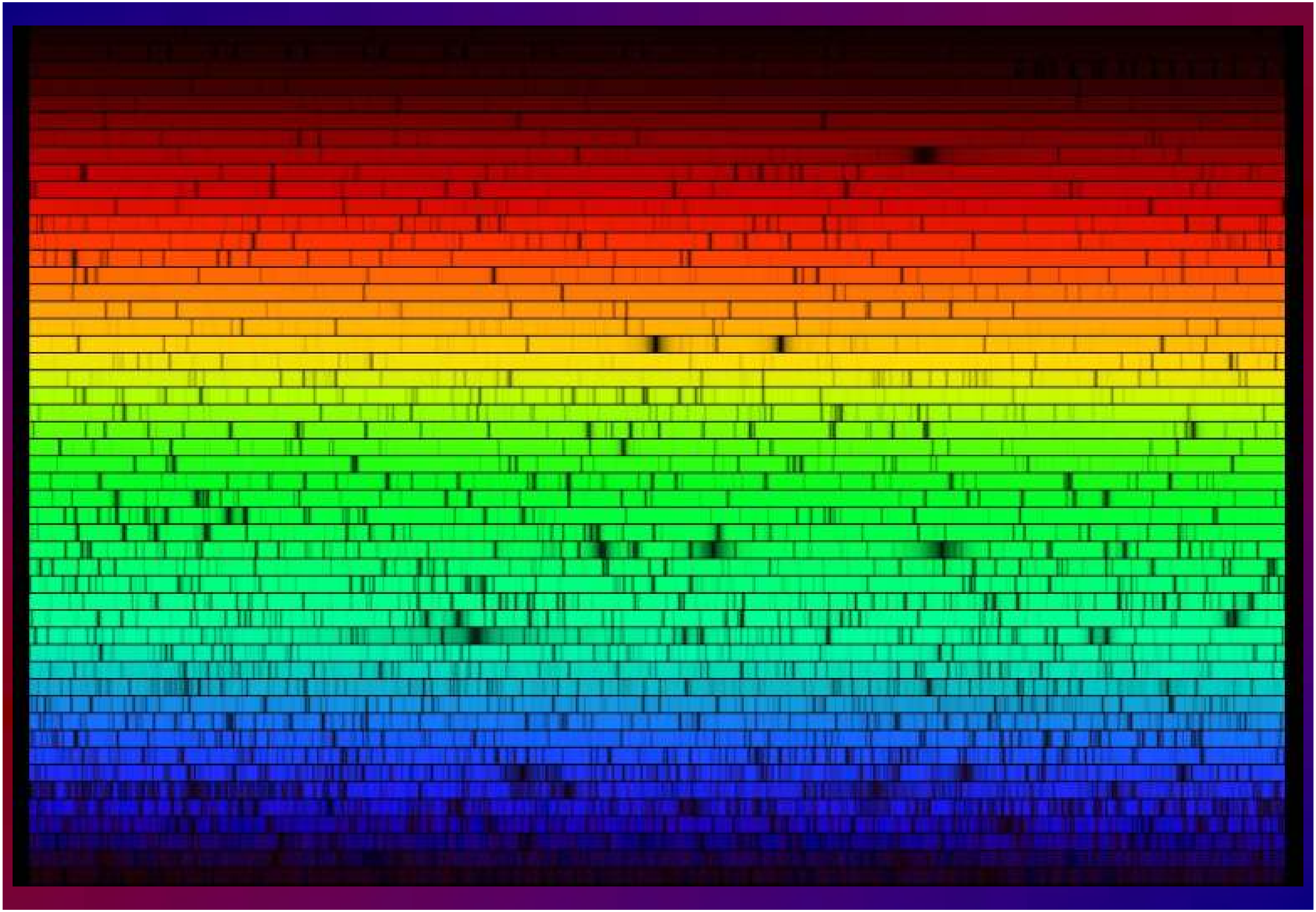
-> Eps Eri, 55 Cnc, 47 UMa ?

Benedict, McArthur, Forveille, et al. 2003

Radial velocity

- Measure the stellar velocity in direction of line-of-sight
- Search for periodic wobble
- Doppler effect!

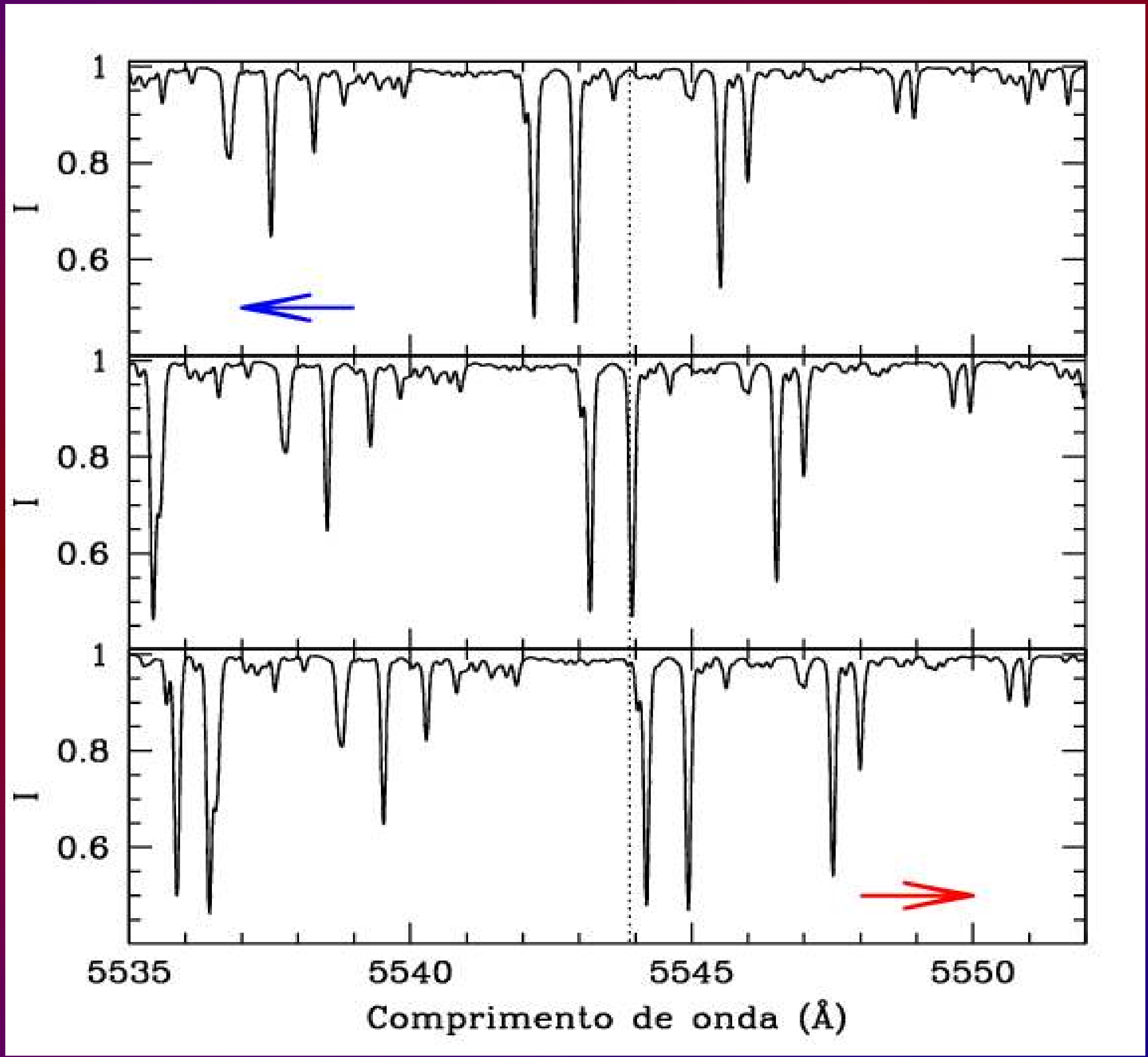




Radial velocity

- Doppler information from spectrum

delta(l)/l = v/c



Elodie programme

Extension of original programme

Swiss-French collaboration

Simultaneous thorium technique

Precision: ~7 m/s

Sample of 350 F-K close dwarfs (magnitude limited)

(Mayor & Queloz 1996)

Observatoire de Haute-Provence 193 cm

19 planets

$m_2 \sin i < 10\ M_{Jup}$

Lick Survey (1992-…)

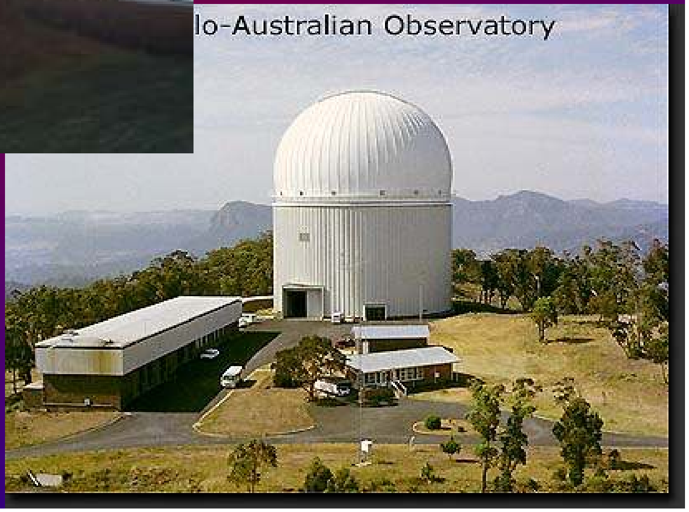
120 stars

Marcy & Butler
Rapid confirmation of 51 Peg
3 planets "in their drawer"
(55Cnc, 47UMa, UpsAnd)

Iodine cell technique
Precision: ~3 m/s
-> ~27 planets

-> Keck programme
S. Vogt, D. Fischer, ….
~ 1000 stars
~ 30 planets

-> AAT programme
C. Tinney, H. Jones, C McCarthy
200-300 stars
~ 17 planets

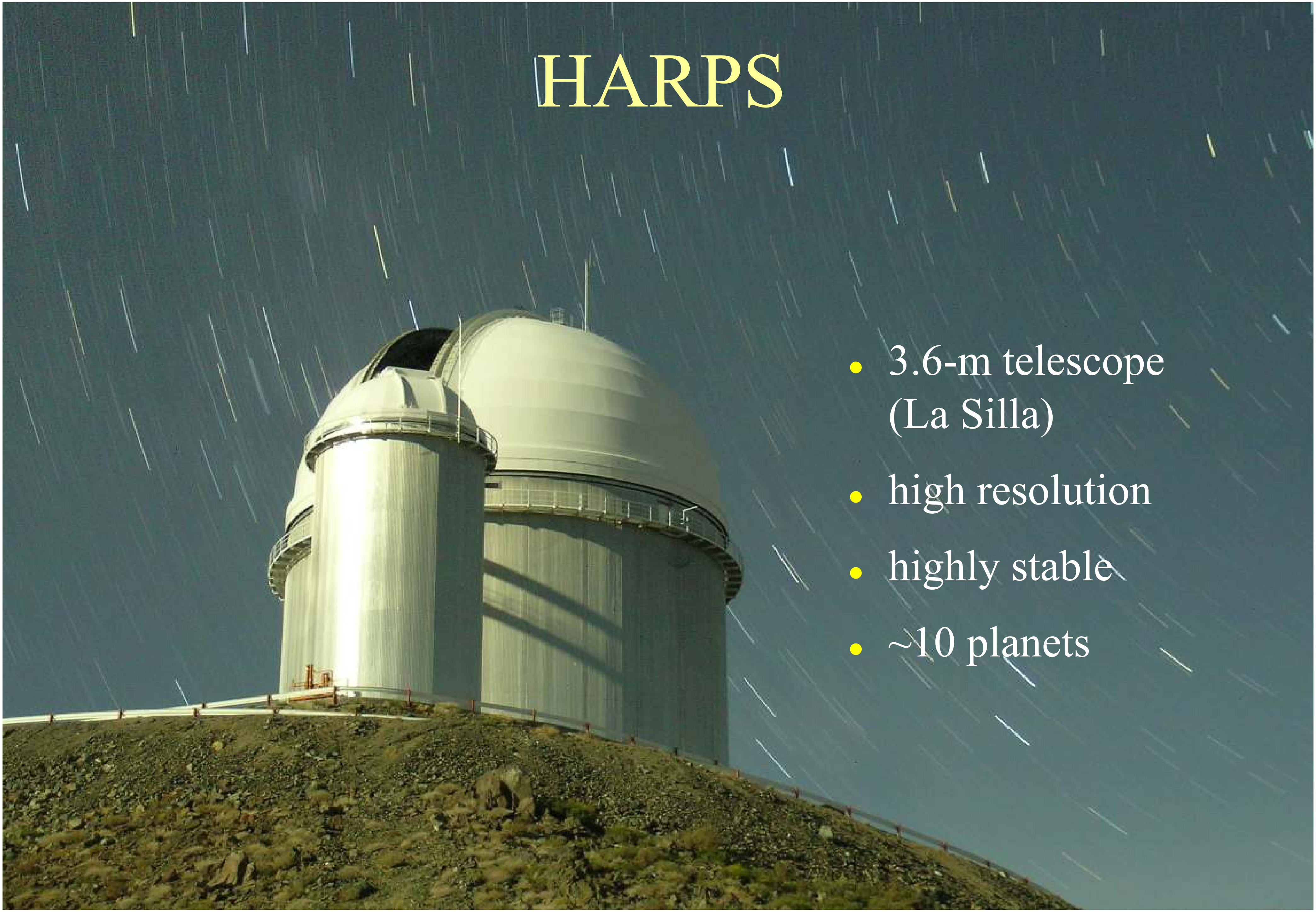


Euler+Coralie – La Silla (1998-...)

M. Mayor, S. Udry, D. Queloz
F. Pepe, D. Naef, N.C. Santos

1.2-m Euler Swiss telescope
Simultaneous thorium technique
Precision: ~3 m/s
-> Photon-noise limited (-> 3-10 m/s)
Volume-limited sample: 1650 F8-M0 dwarfs
(Queloz et al. 2000, Udry et al. 2000)

~ 40 PLANETS


HARPS
3.6-m telescope (La Silla)
high resolution
highly stable
~10 planets

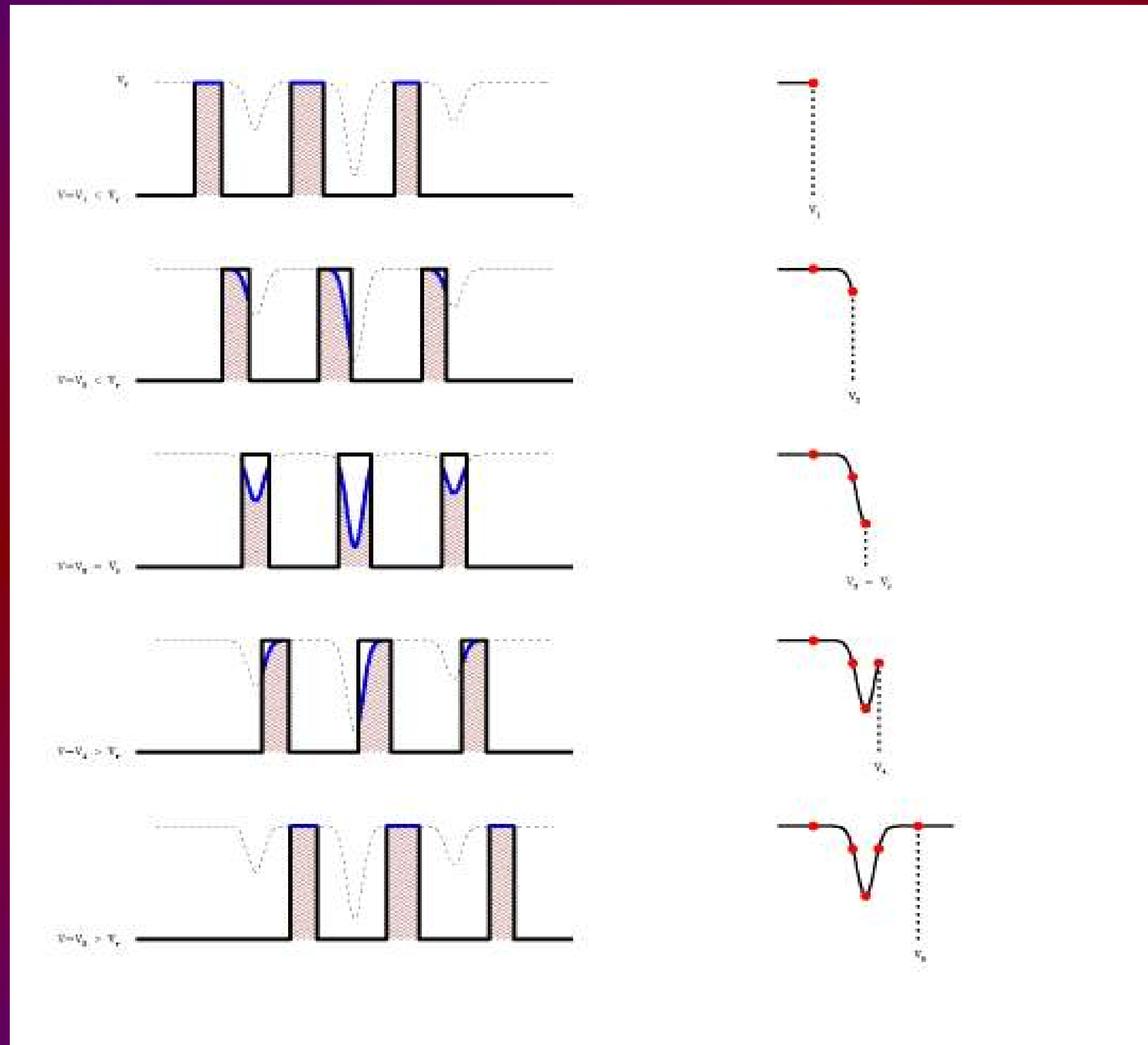
How to derive precise shifts?

- Need for very high precision in wavelength scale
- delta(l) ~10^{-5} (for 5m/s at 5000A)
- Use statistically the spectral information
  - many lines
- Use stable reference (ThAr lamp, Iodine cell)

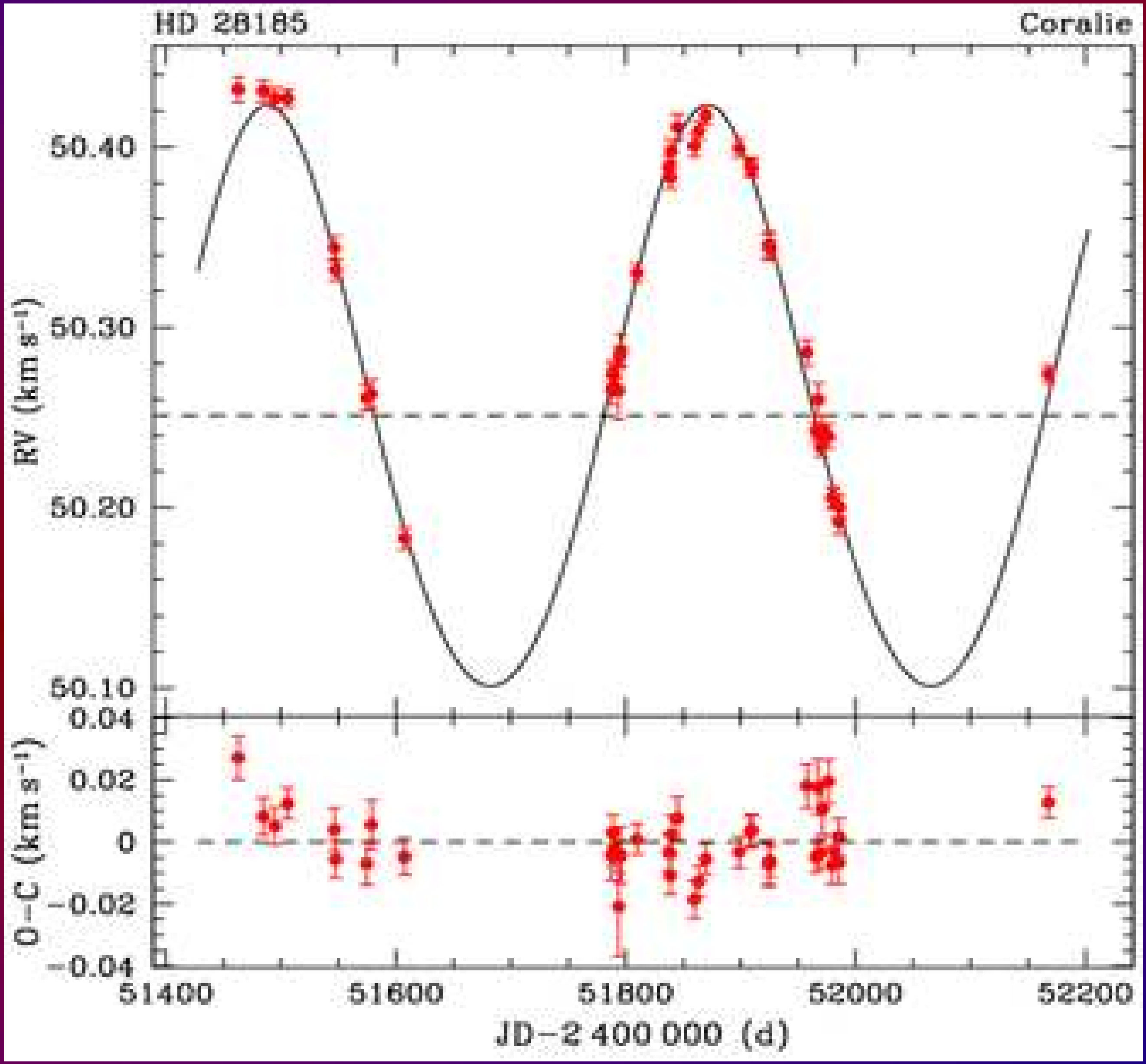
Cross-Correlation technique

CCF – “average spectral line”

Position of CCF -> velocity!



Example RV curve:



Some basic equations

RV semi-amplitude:

$$K(km/s)=212.9\ (M_1/P)^{1/3}(q/(1+q)^{2/3})(\sin(i)/(1-e^2)^{1/2})$$

$[q=M_2/M_1]$

Mass Function:

$$F(m)=M_2^3\sin^3(i)/(M_1+M_2)^2=$$

$$=K_{1\ km/s}^{3}(1-e^2)^{3/2}\ P_{days}\ 1.036E\text{-}7\ M_{sun}$$

For which stars can we use RV?

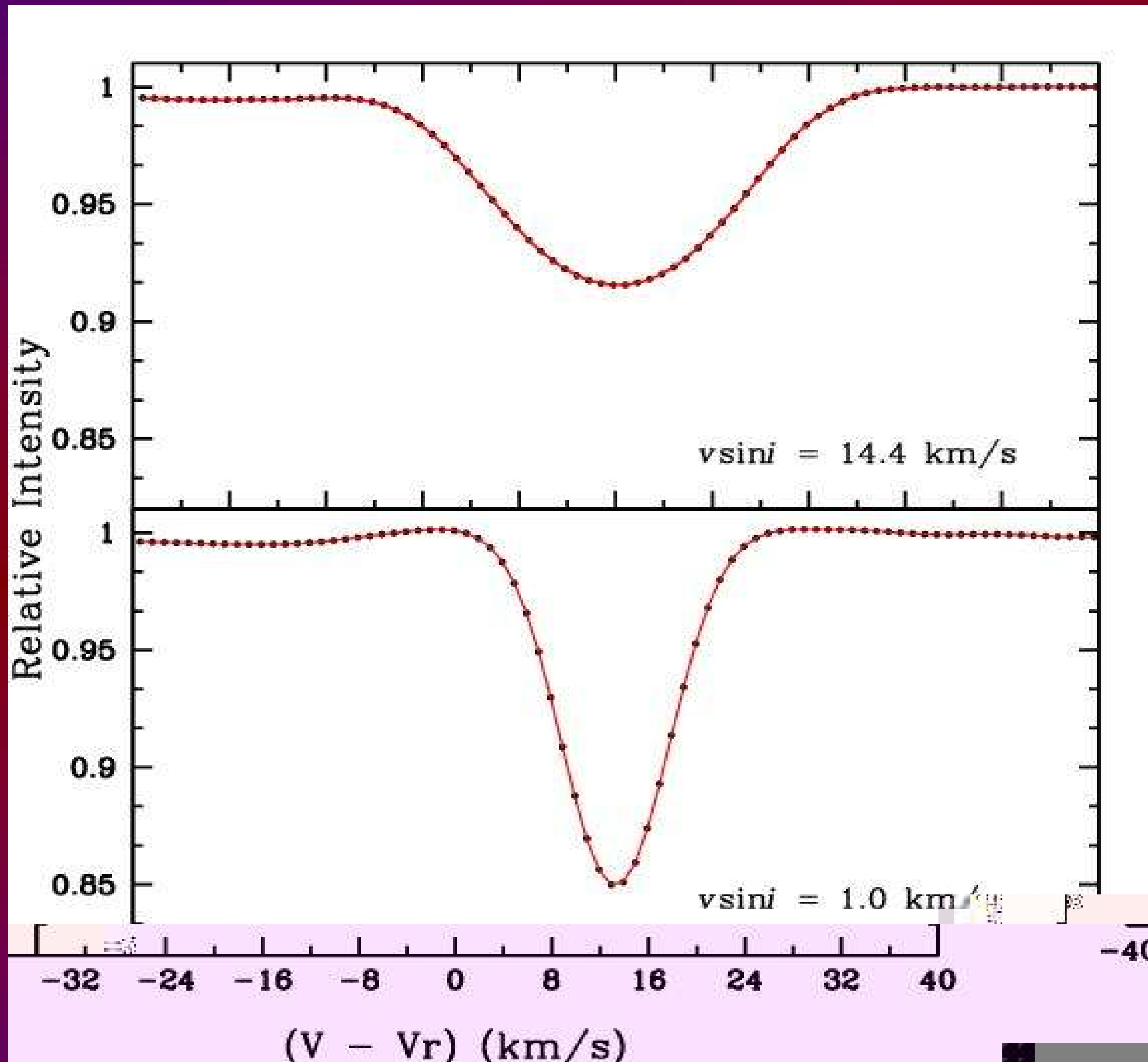
- Mostly solar-type stars
  - Enough lines in stellar spectra!
  - Hot stars do not have narrow lines (not many lines)!
- Young stars: too active!
- Not good for stars that rotate very fast

Stellar limitations to RV technique

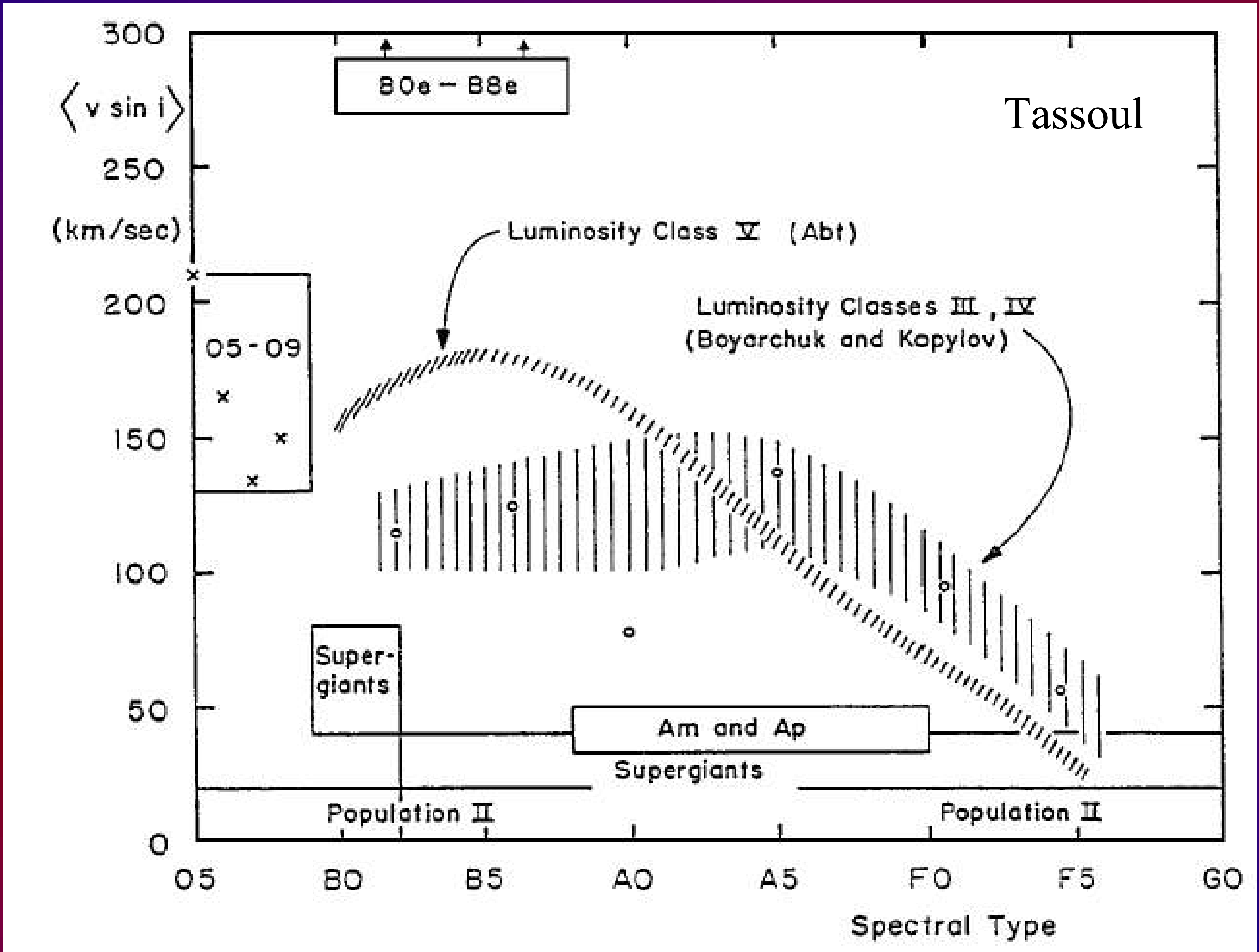
- Stellar rotation
- Photospheric spots and convection
- Stellar blends
- Stellar pulsation
- How to diagnose?

Stellar rotation

- We observe disk integrated light
- Lines become wider when vsini is taken into account
- lower RV precision for high rotating stars (early-type, young stars)

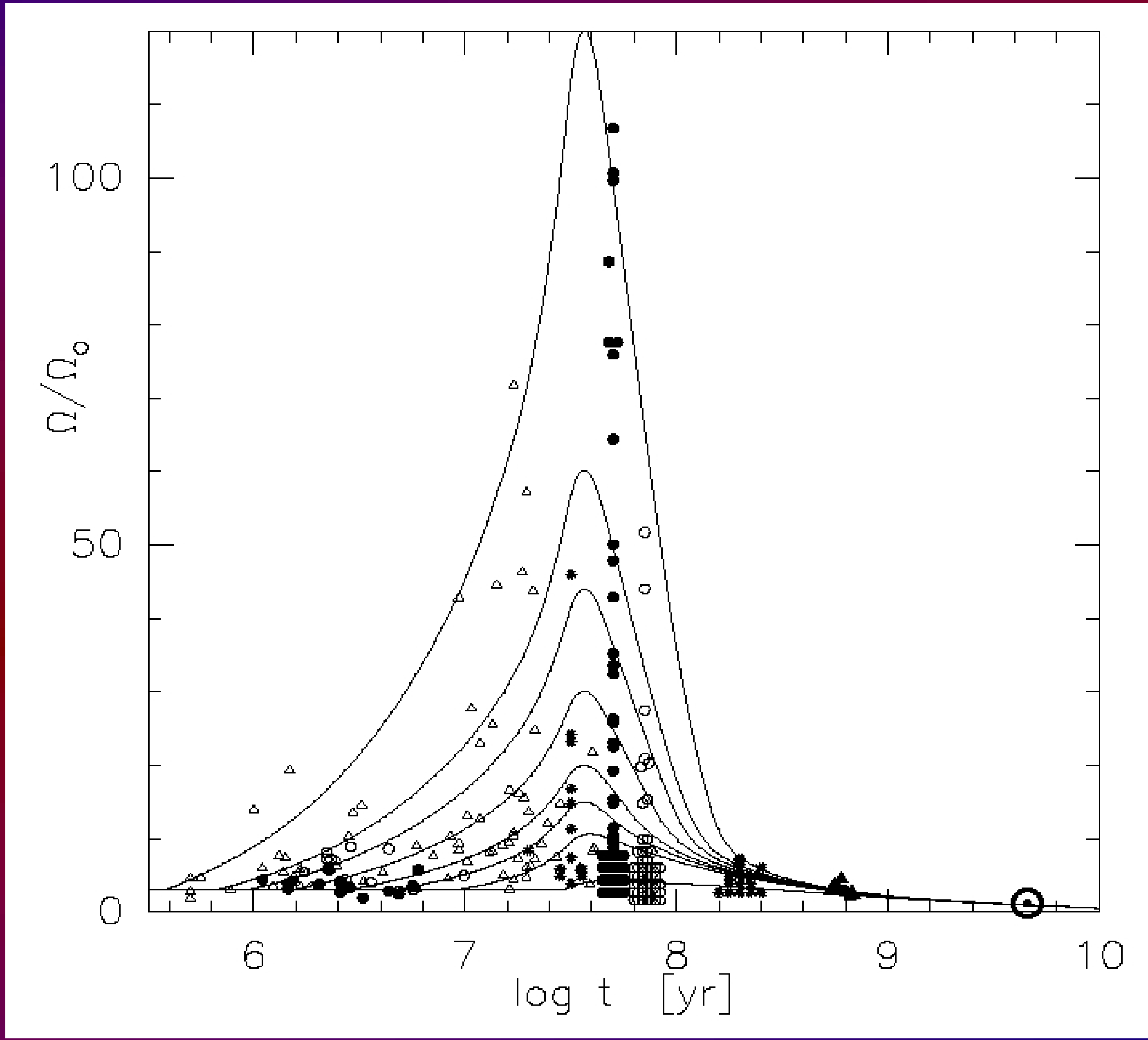


Stellar rotation across the HR diagram

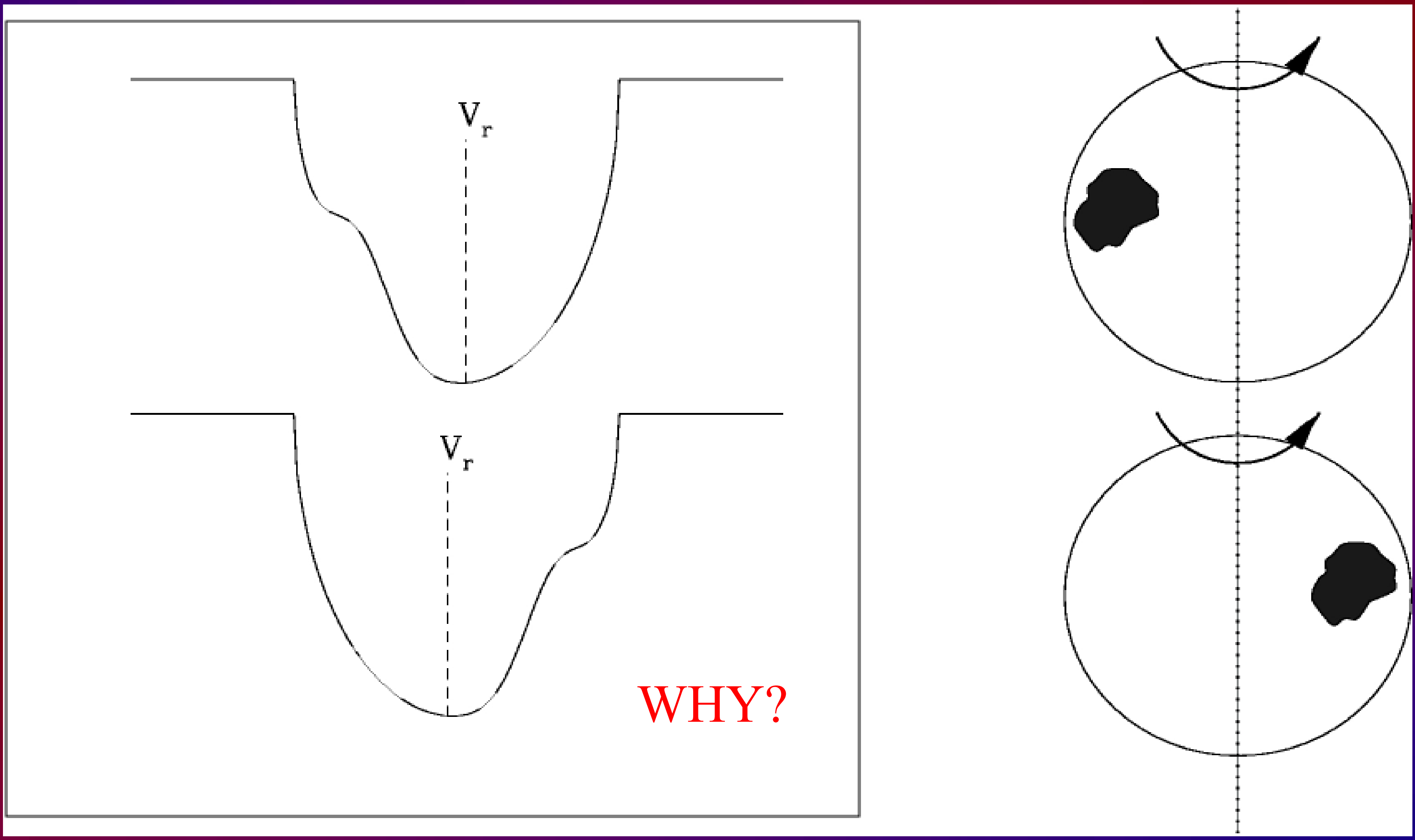


Rotational evolution of T Tauris

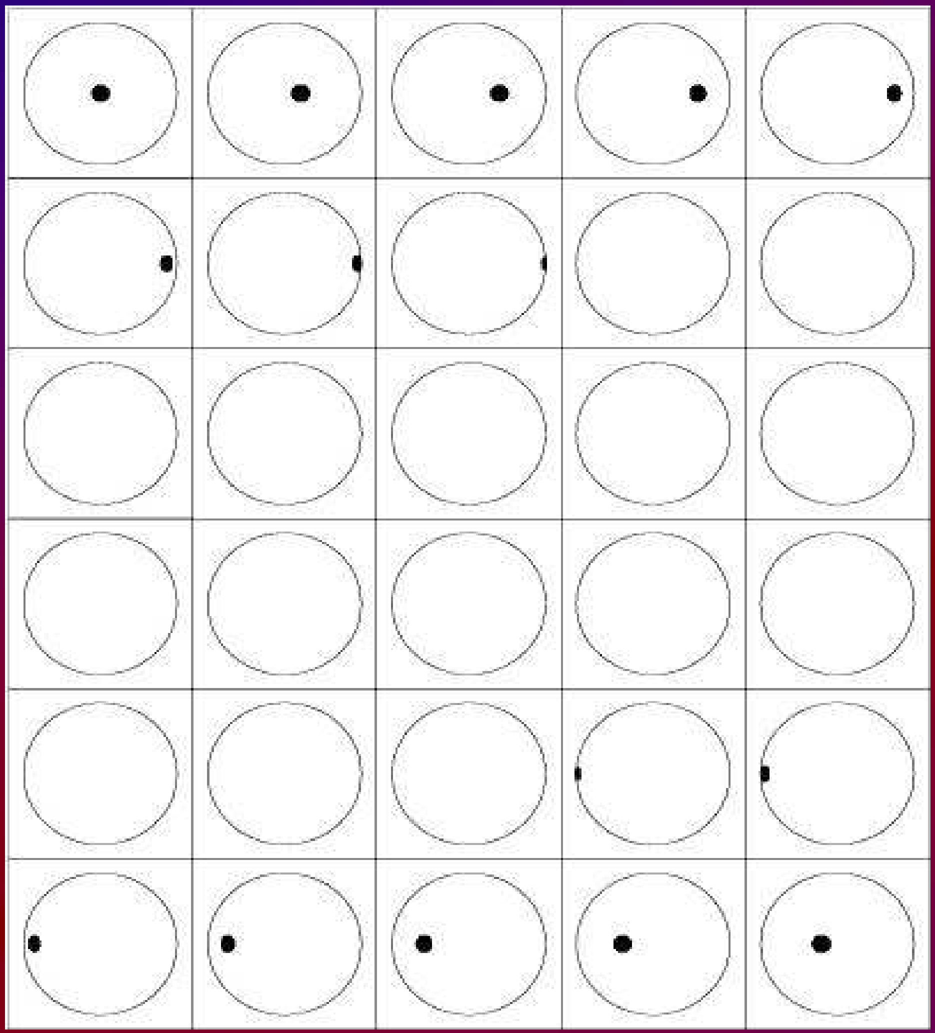
(Bouvier et al. 1997)

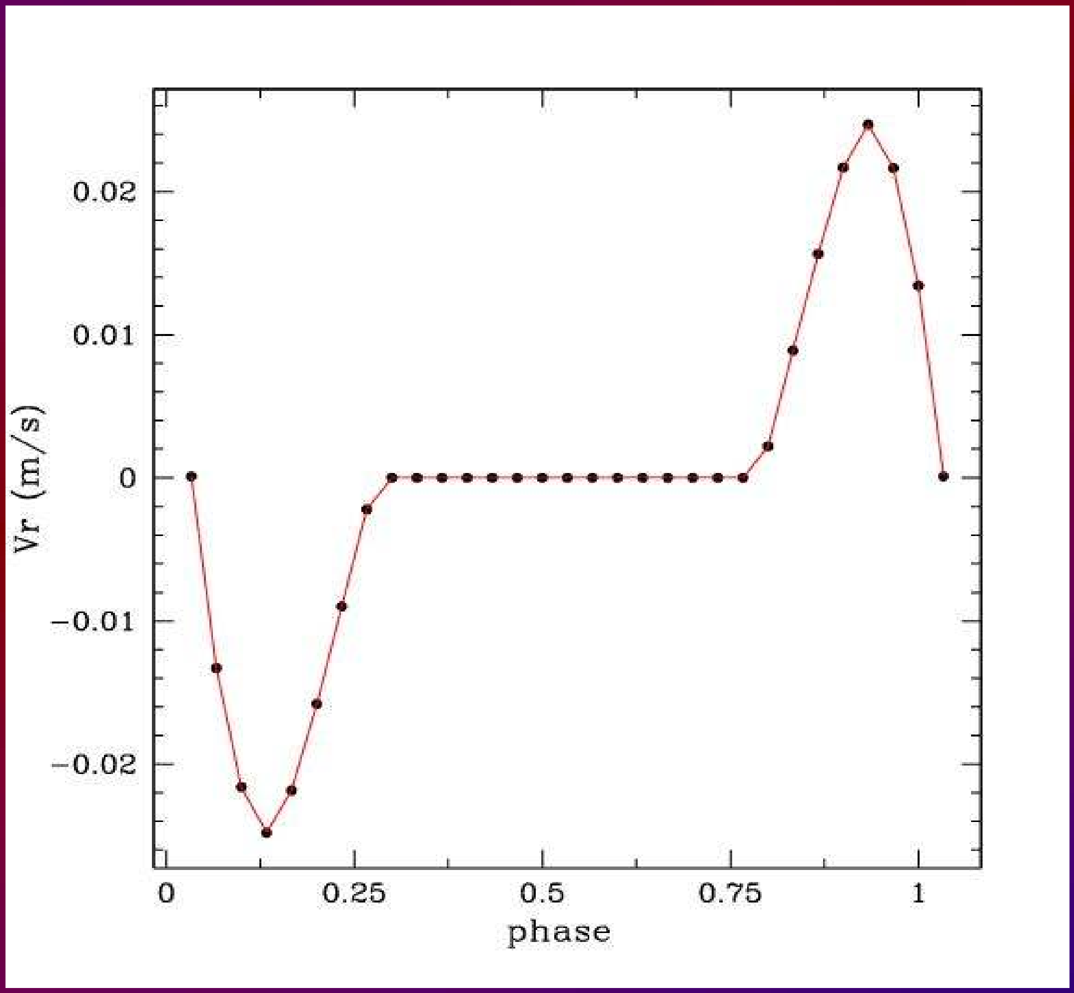


Photospheric features (spots & conv. inhomogeneities)



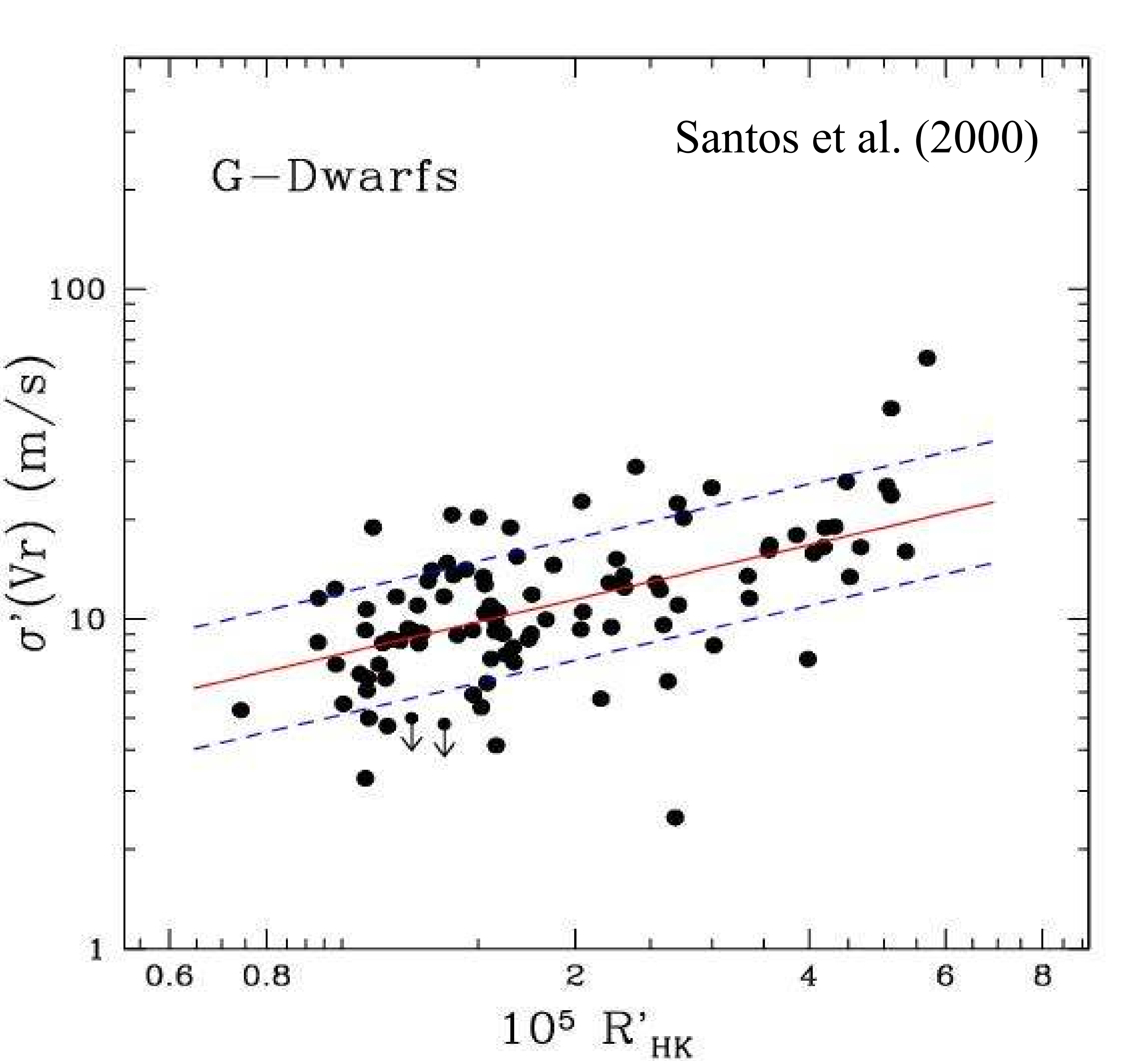
Spots and RV





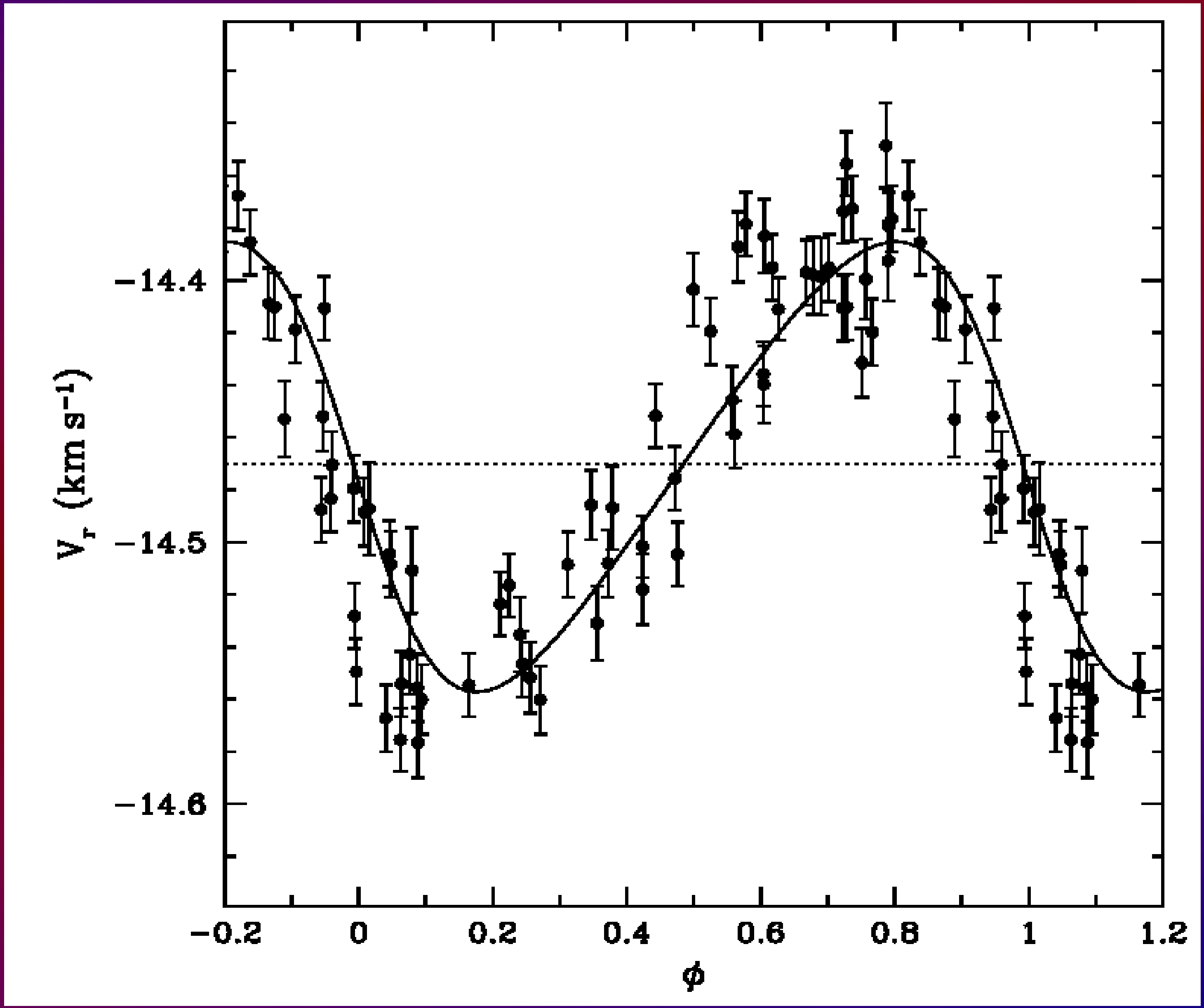
A[m/s]~6.5 vsin(i) $f_s^{0.9}$ (Saar & Donahue 1997)

Stellar activity induces RV noise



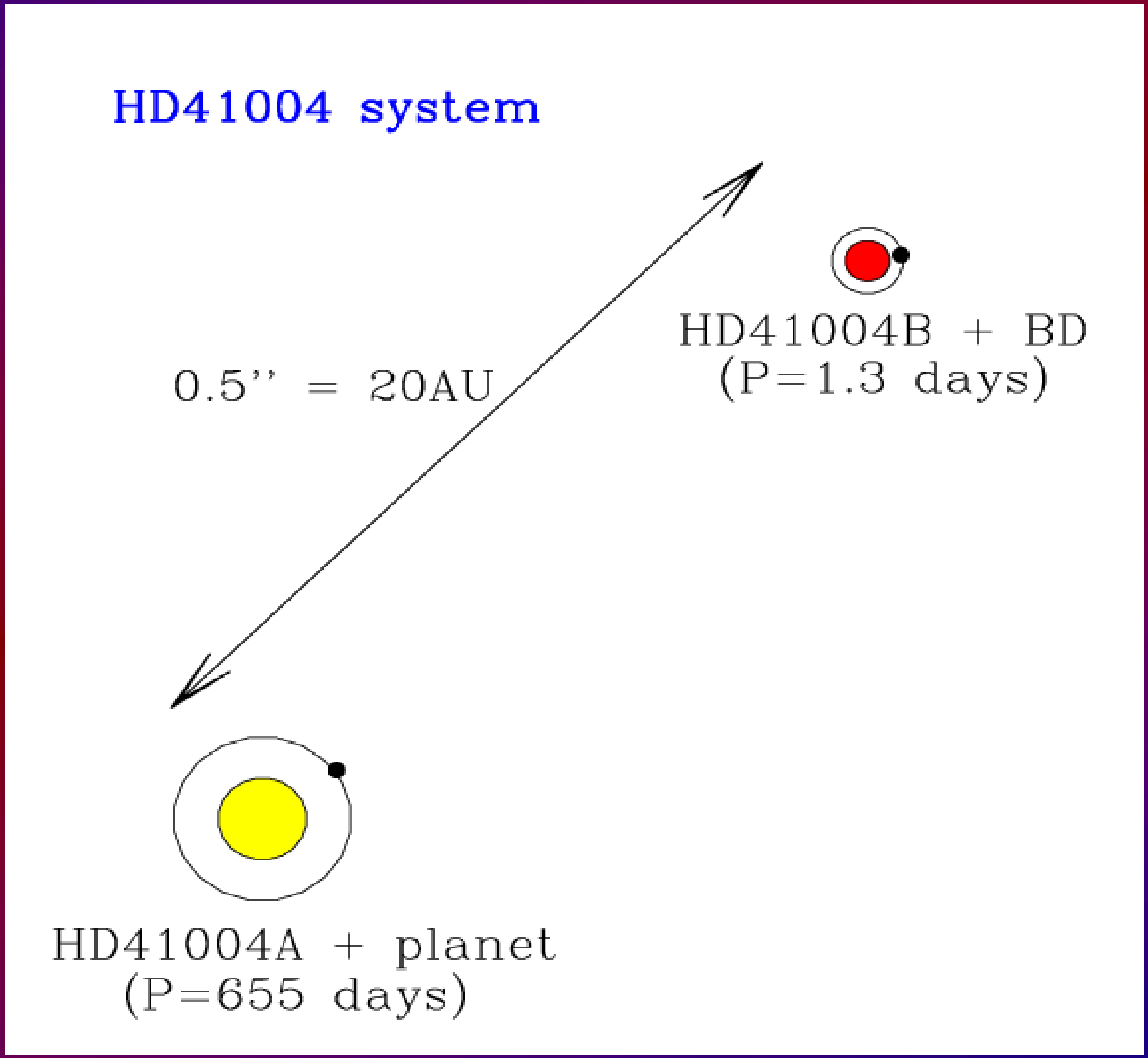
Spots can mimic planets!

- HD166435 (Queloz et al. 2001)
- Spots cause a periodic RV variation similar to the one expected by the presence of a planet!

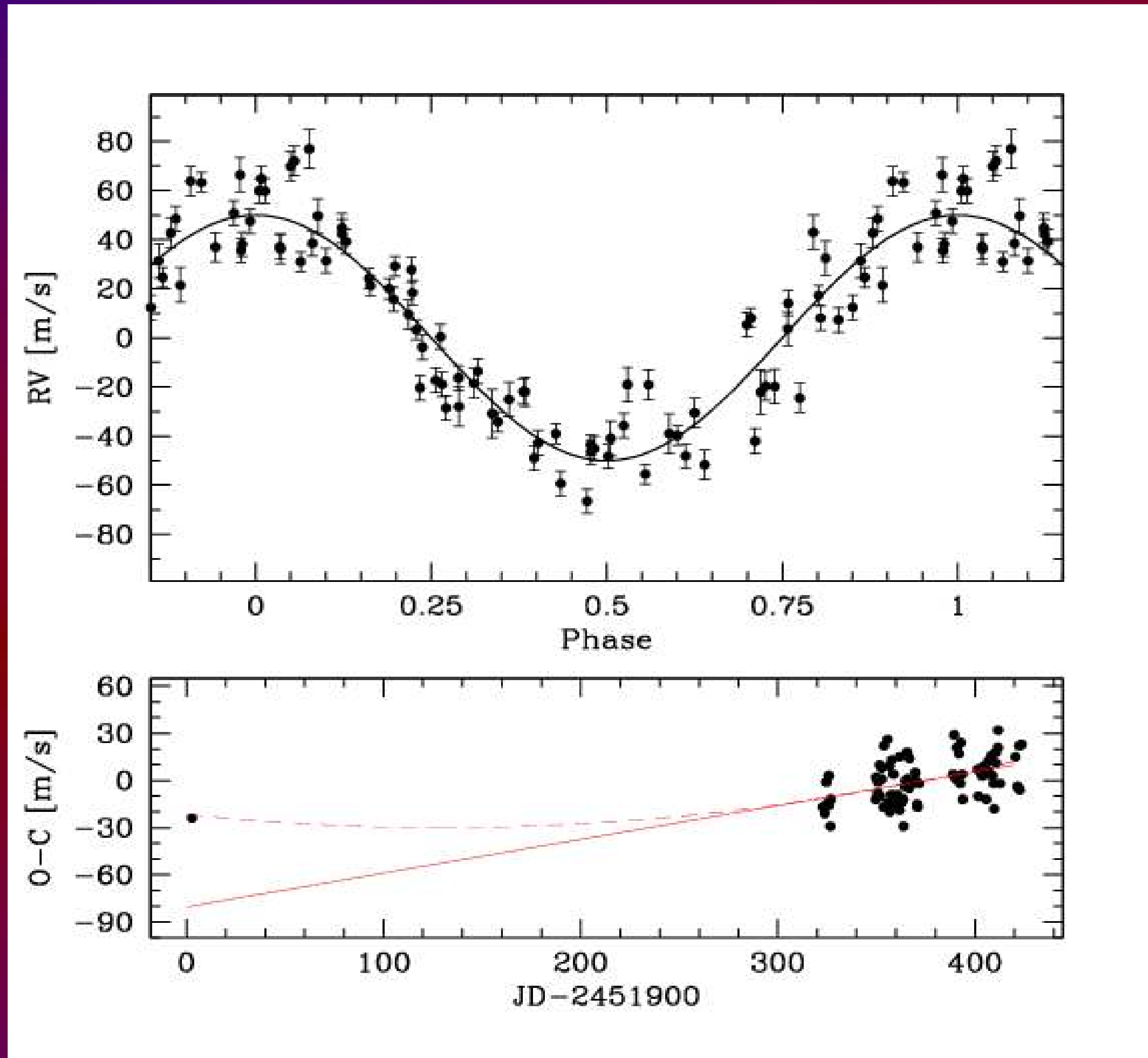


Stellar blends

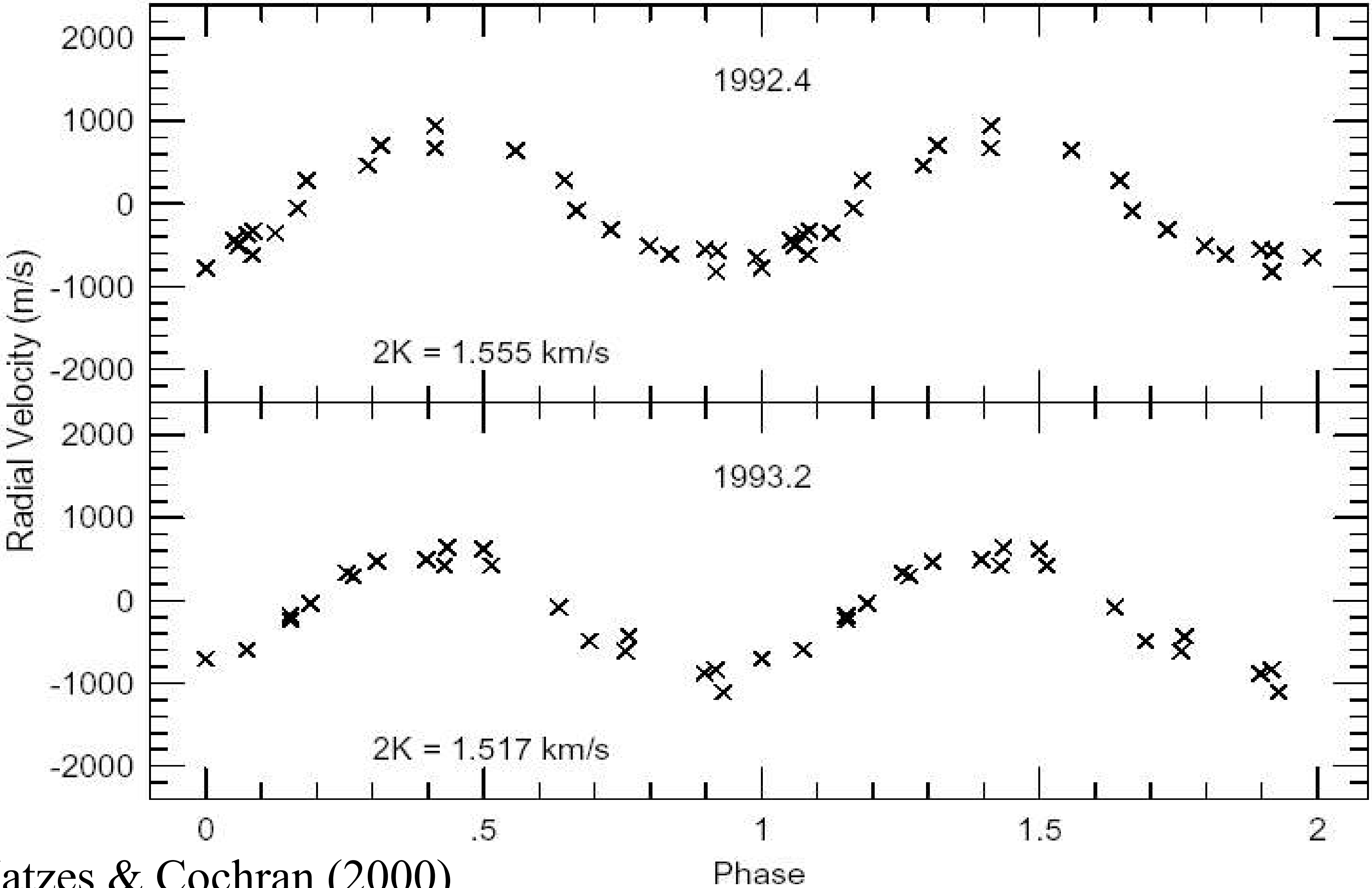
HD41004 (Santos et al. 2002)



Stellar blends can mimic RV signature of planet!



Stellar pulsation



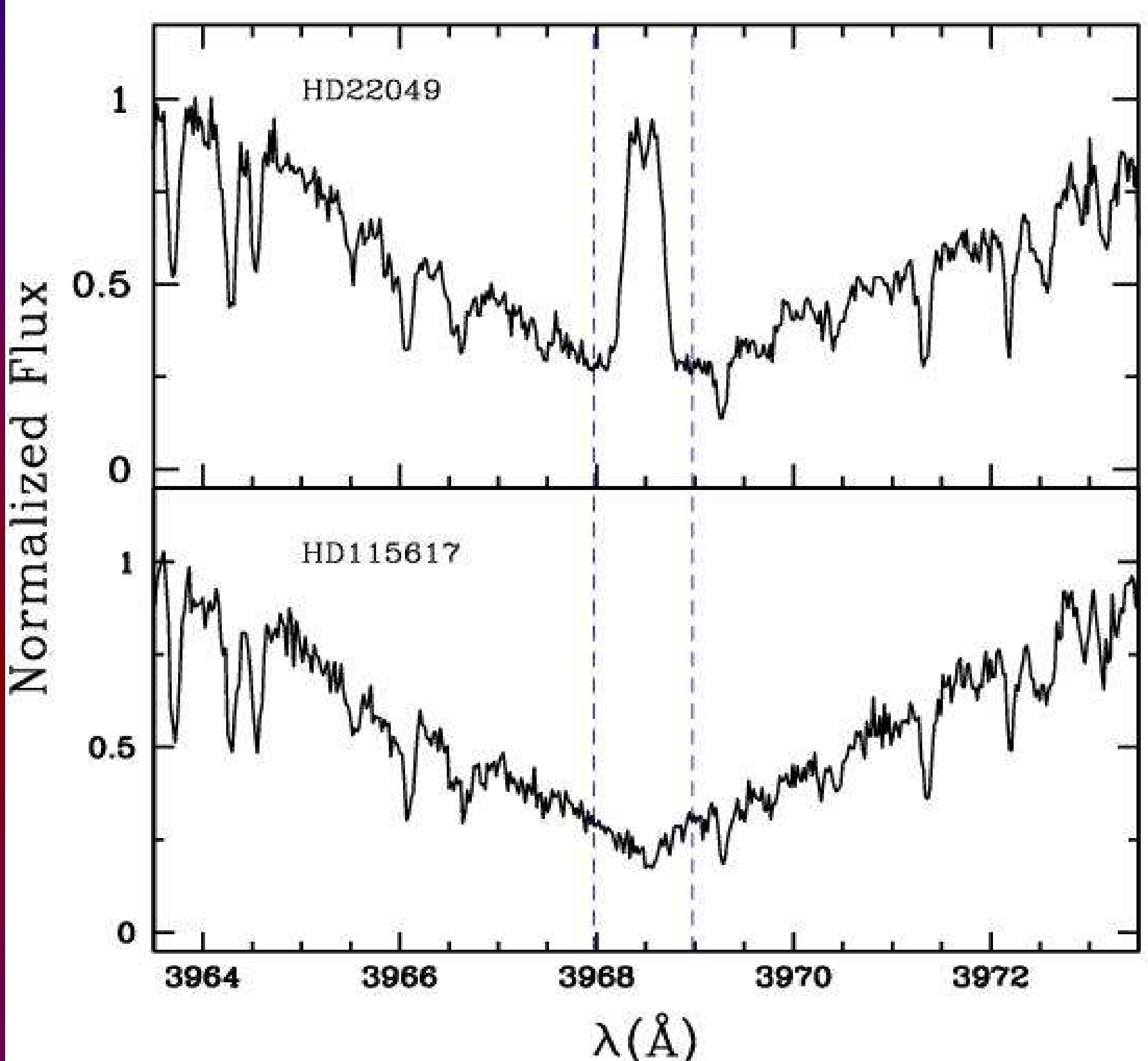
Hatzes & Cochran (2000)

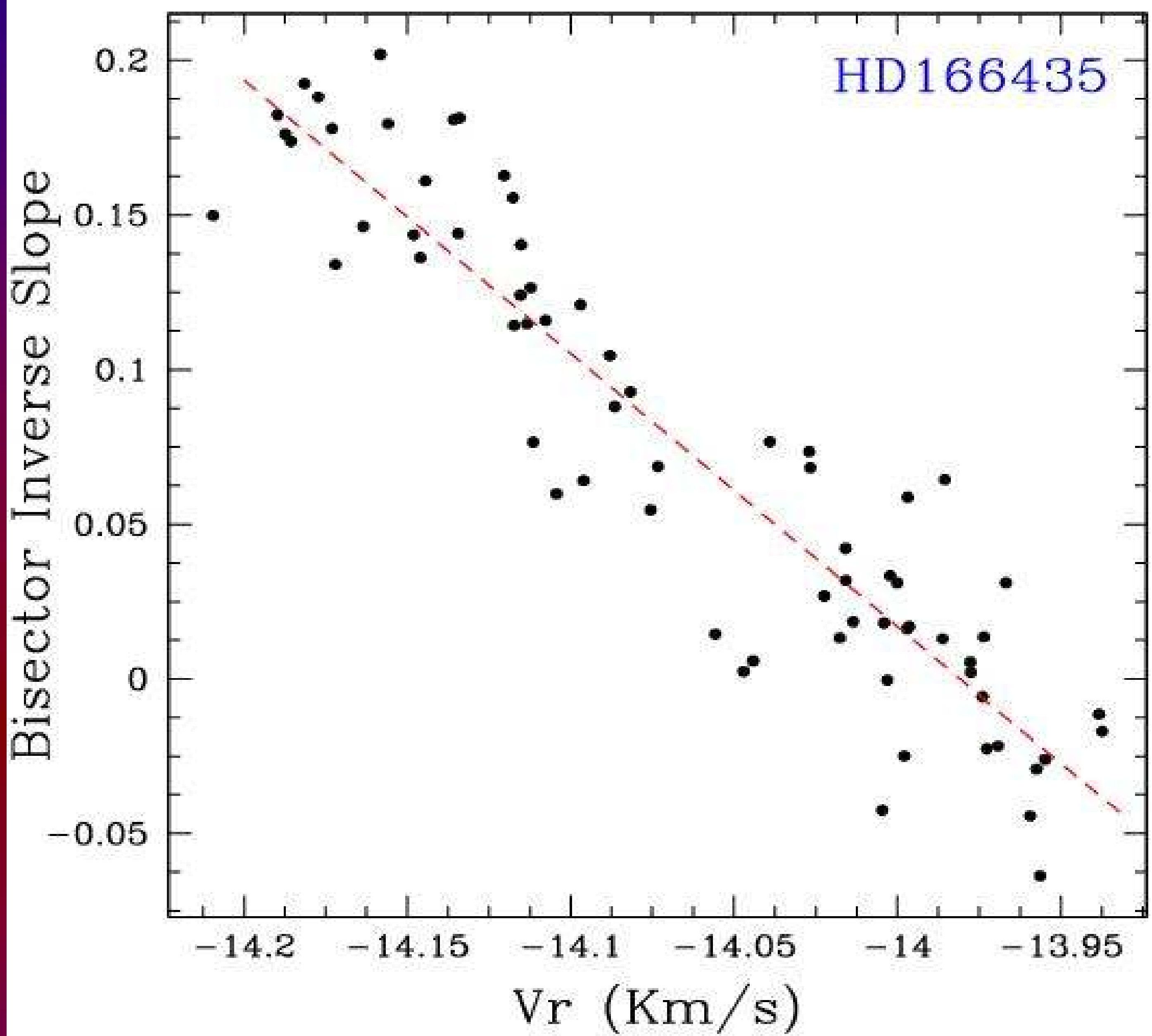
How to diagnose these cases?

- Photometry
  - Pulsation, spots
  - Note: pulsation is not matter for solar-type dwarf
- Stellar Activity
  - Spots (active regions)
  - Problem: not very sensitive
- Line profiles (bisectors)
  - Spots, convection, blends, pulsation
  - Problem: for low vsini, not sensitive to spots

Stellar activity

CaII H and K line emission (S Index; Vaughan 1978)




HD166435
Bisector Inverse Slope
Vr (Km/s)
0.2
0.15
0.1
0.05
0
−0.05
−14.2
−14.15
−14.1
−14.05
−14
−13.95

Stellar blends

Induce line-profile variations and RV variation