Dynamical Methods: Radial Velocity and Astrometry

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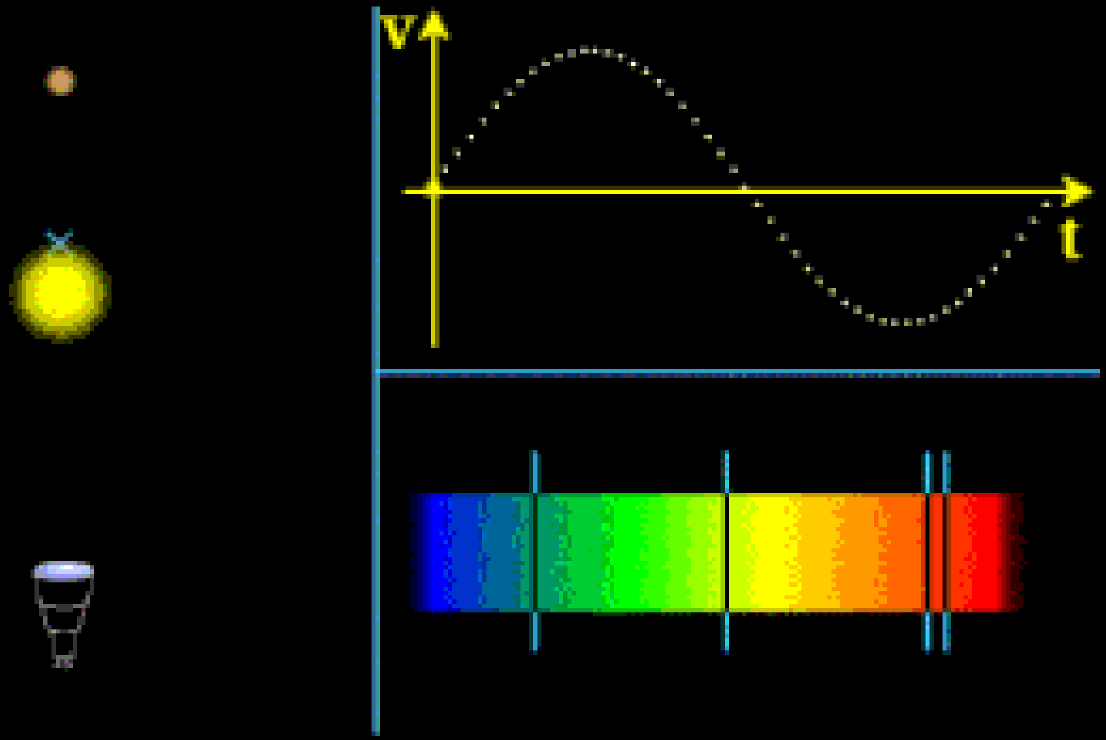
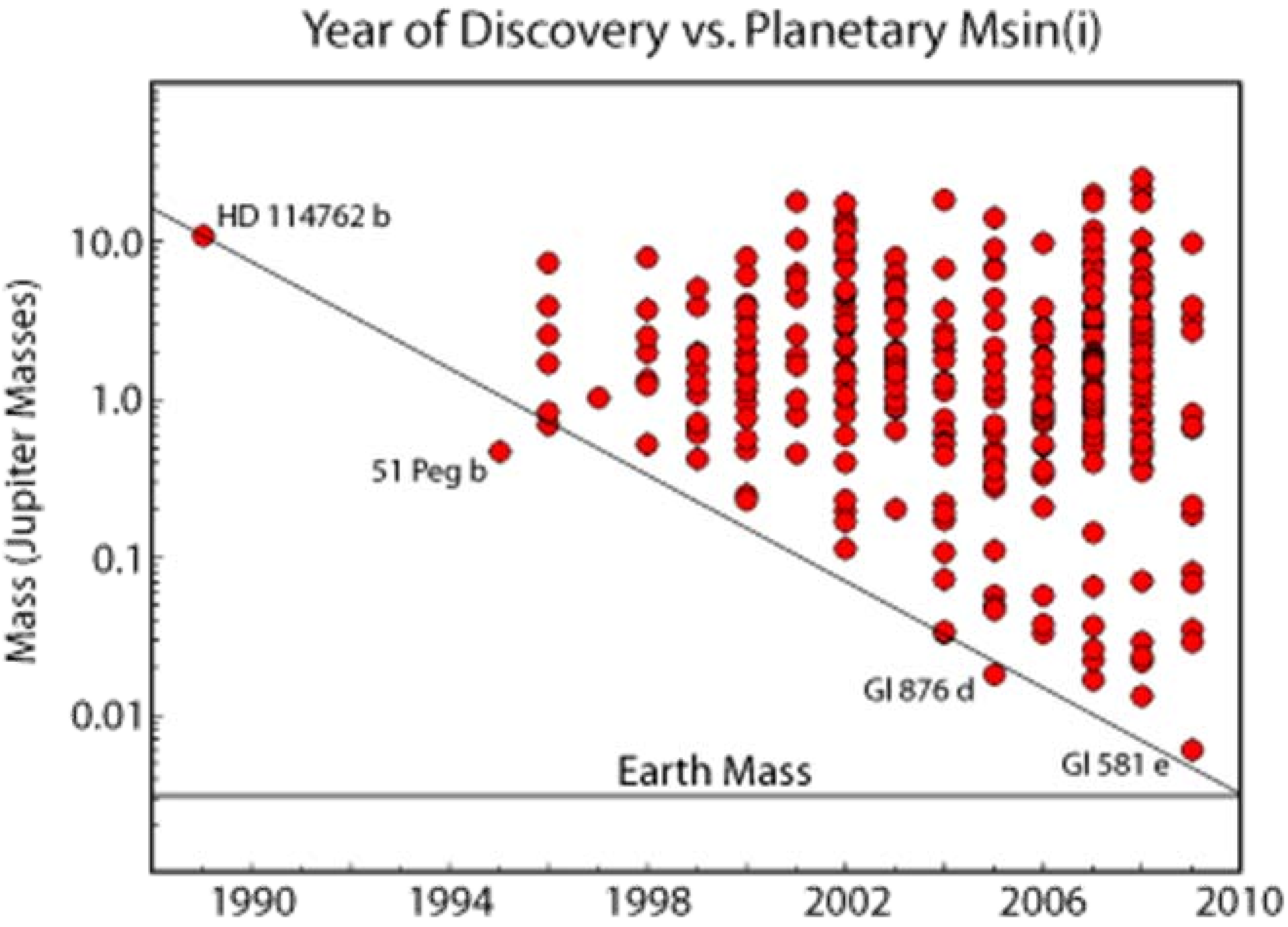


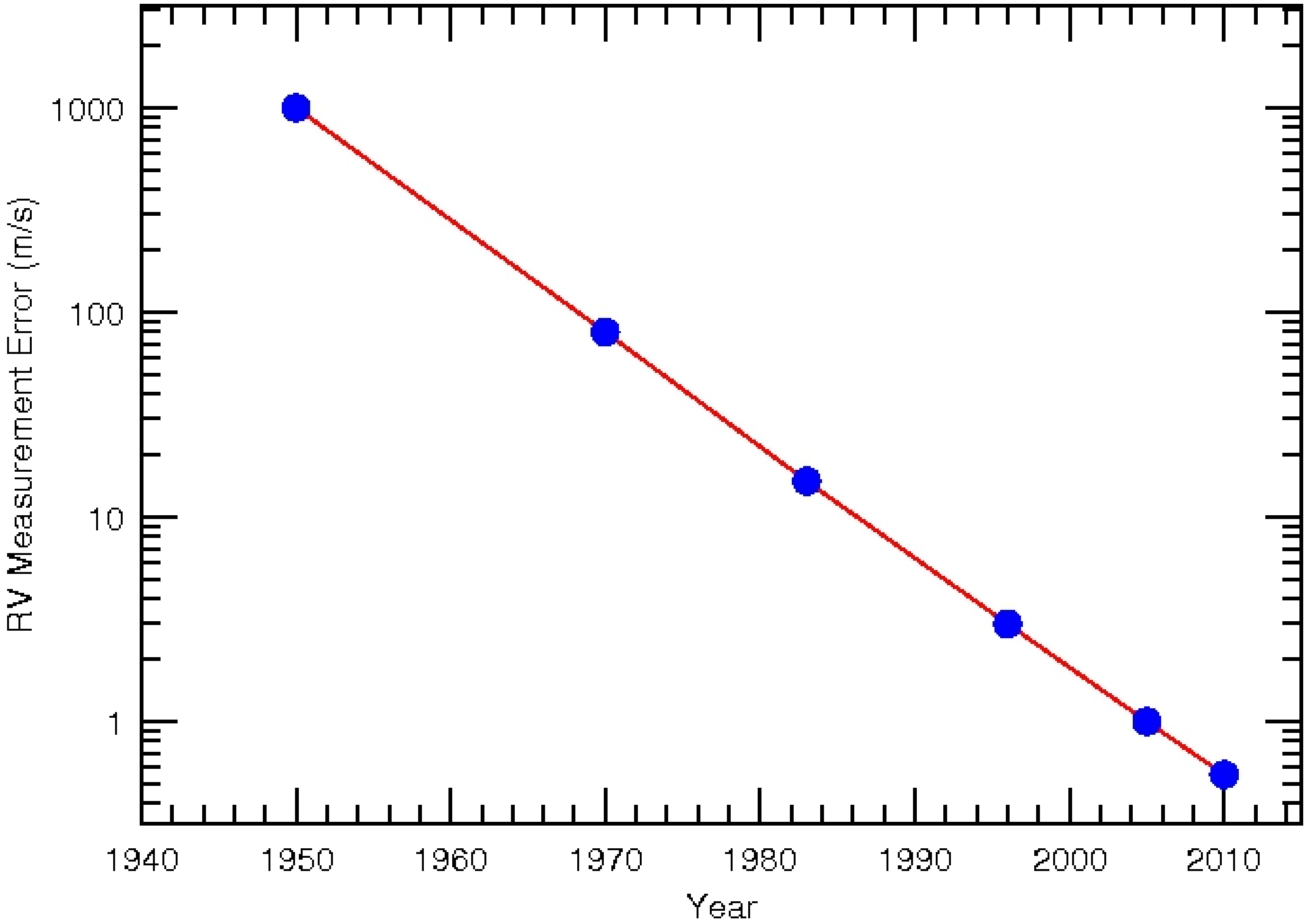
„How low can you go?"

Chubby Checker „Limbo Rock"

I. Radial Velocity Measurements

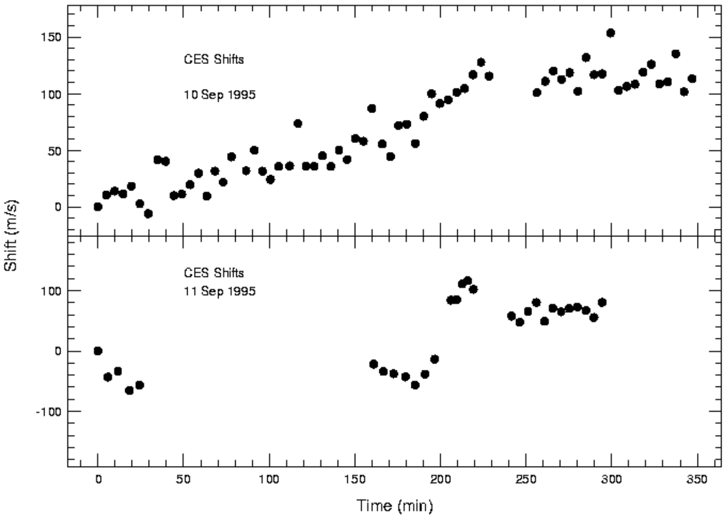


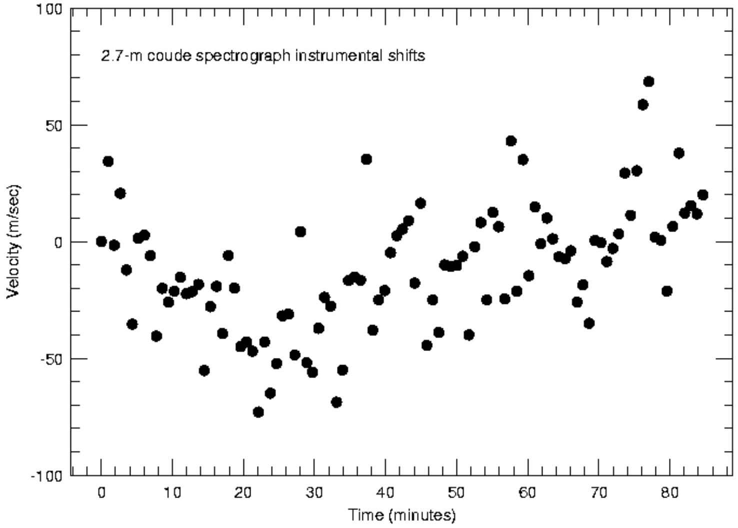
The Evolution in Radial Velocity Precision



RV precision of 10 cm/s by 2023!

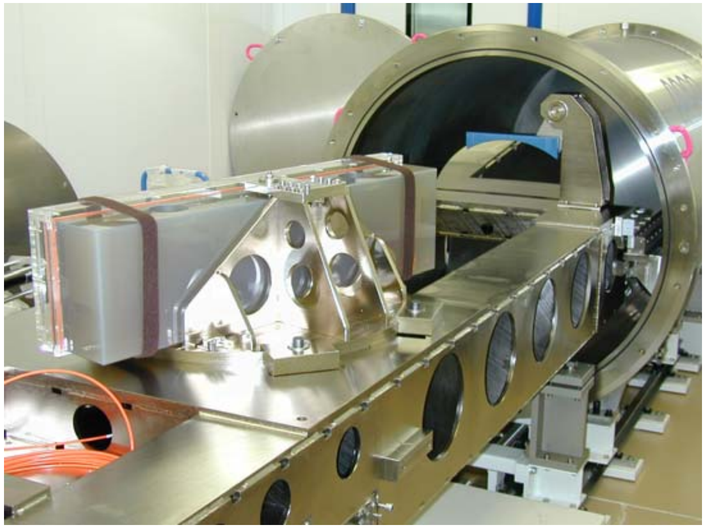
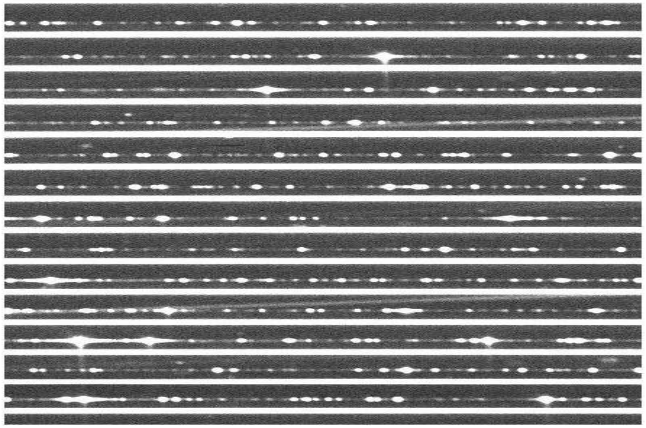
Until 1980 RV measurements were limited by instrumental shifts:



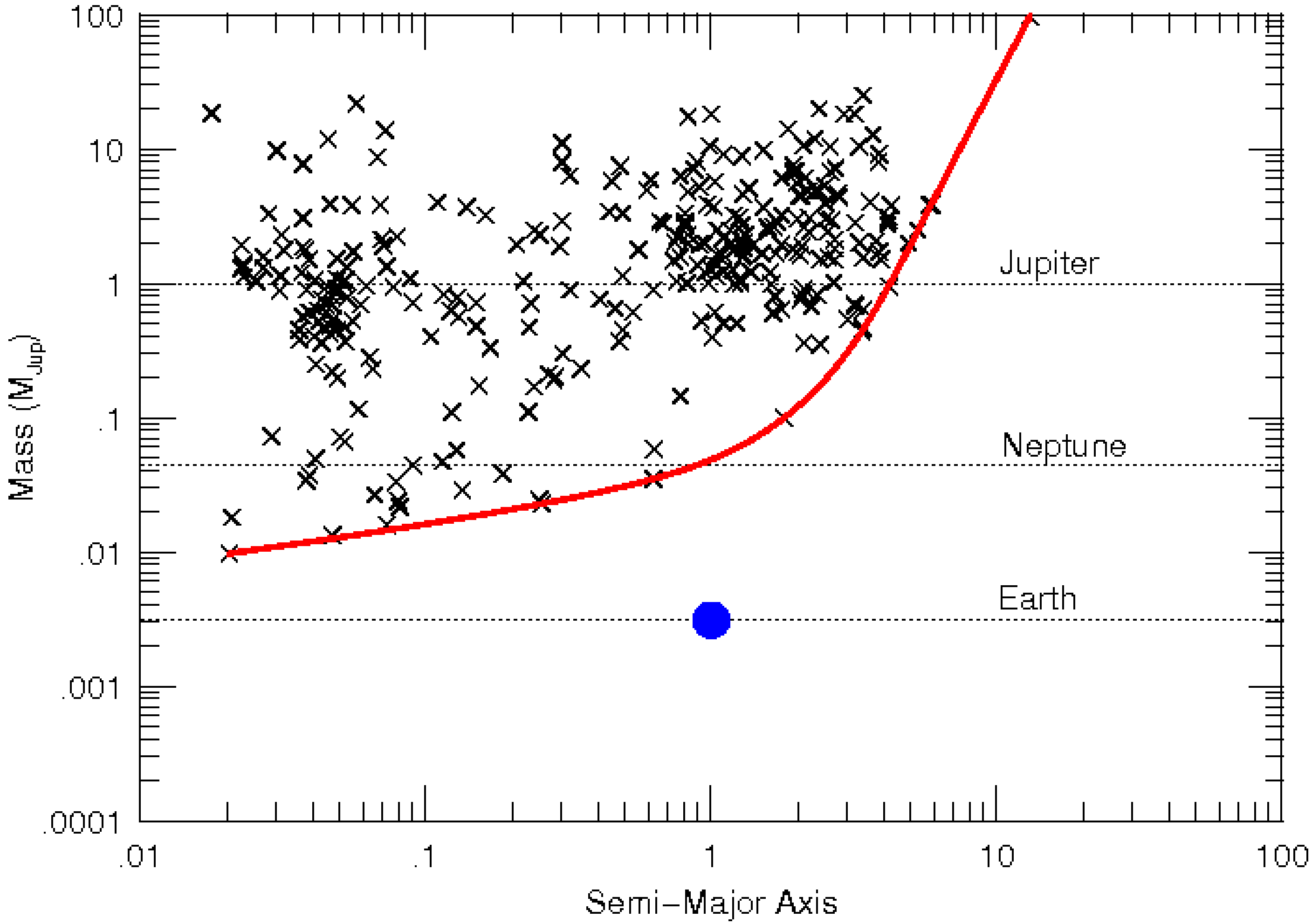


These have been greatly minimized using simultaneous wavelength calibration

Techniques: Simultaneous Th-Ar versus Absorption Cell

Stability		
Wavelength Reference		
Best Precision	**0.5 – 1 m/s**	**1 – 2 m/s**[1] [1]On spectrographs not designed for stability

How far can Radial Velocities take us, or „How low can you go?“



K = 10 cm/s

Can we detect an Earth at 1 AU?

Can we Limbo lower?

The total radial velocity error is the sum of a complete error budget.
A stable wavelength reference is just one component

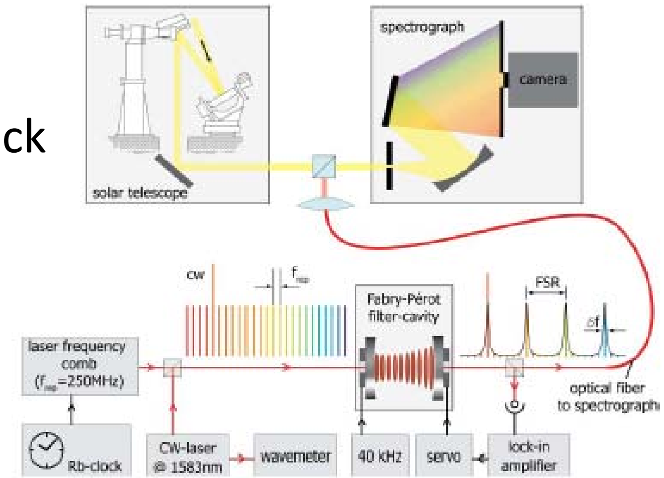
1. Guide errors (largely solved with scramblers)
2. Stable wavelength reference
3. Changes in the optical system (changes in the instrumental profile)
    a) Stabilize the spectrograph (HARPS)
    b) Monitior IP (Iodine, Laser Comb)
4. The Detector (often ignored)

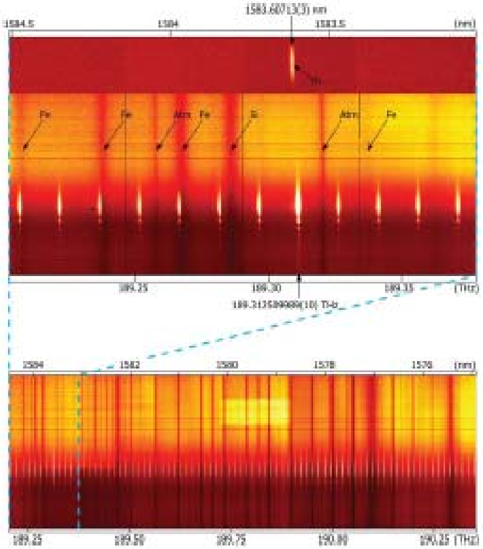
5. Proper motion/barycentric corrections
6. Intrinsic stellar variability

„Limbo lower now, Limbo lower now…“

2. Improved Wavelength Reference

- Laser Frequency Combs
  - Provides a series of perfectly equidistant lines
  - Covers a large wavelength domain
  - Stabilized at the 10^{-11} to 10^{-15} level
  - The absolute reference linked to an atomic clock

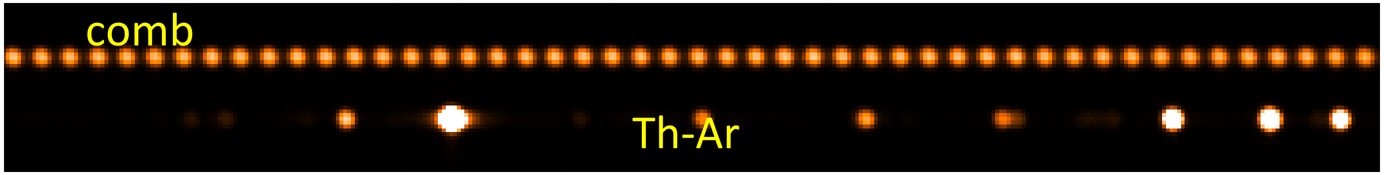




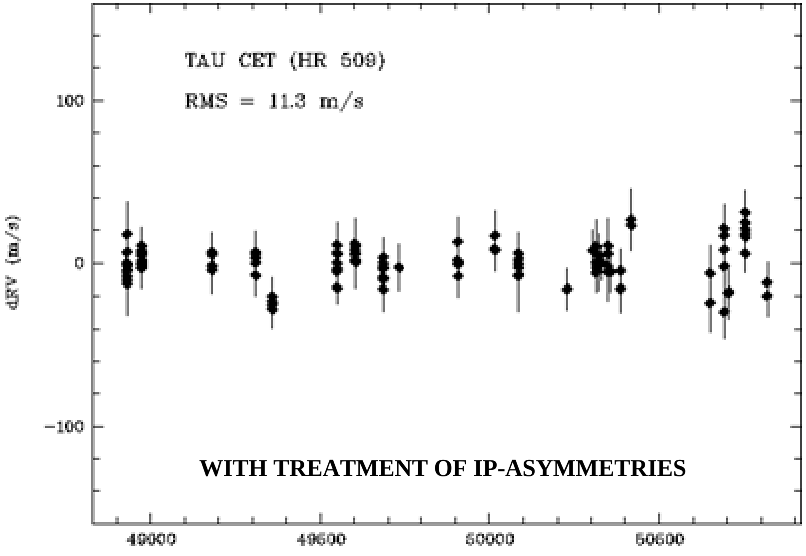
System has been developed and test in HARPS shows excellent performances:

Astro-comb: ~450 lines per order
5cm/sec PHOTON NOISE LIMITED stability in short term

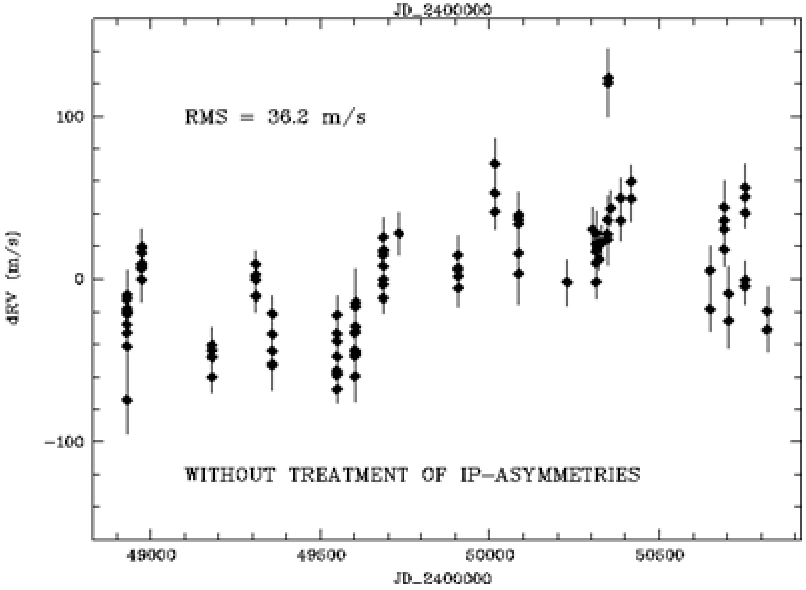
Th-Ar: ~150 lines per order
24cm/sec

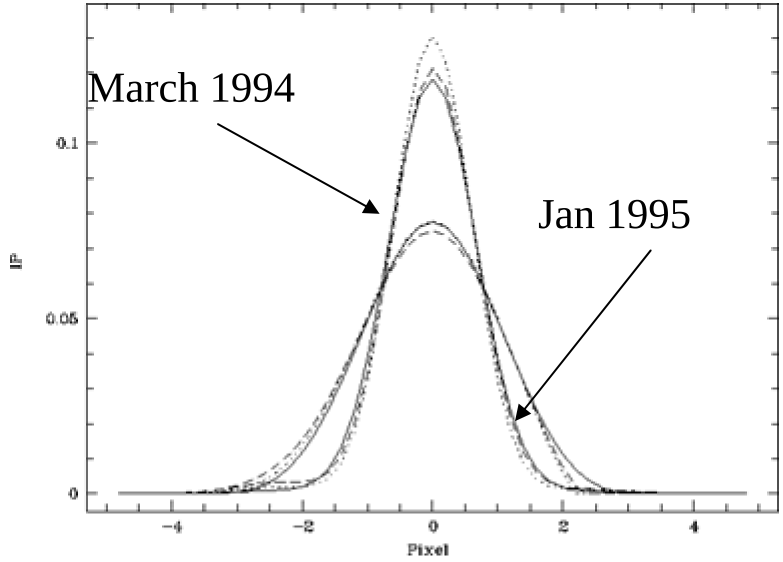


3. Stable Instrumental Profile



WITH TREATMENT OF IP-ASYMMETRIES

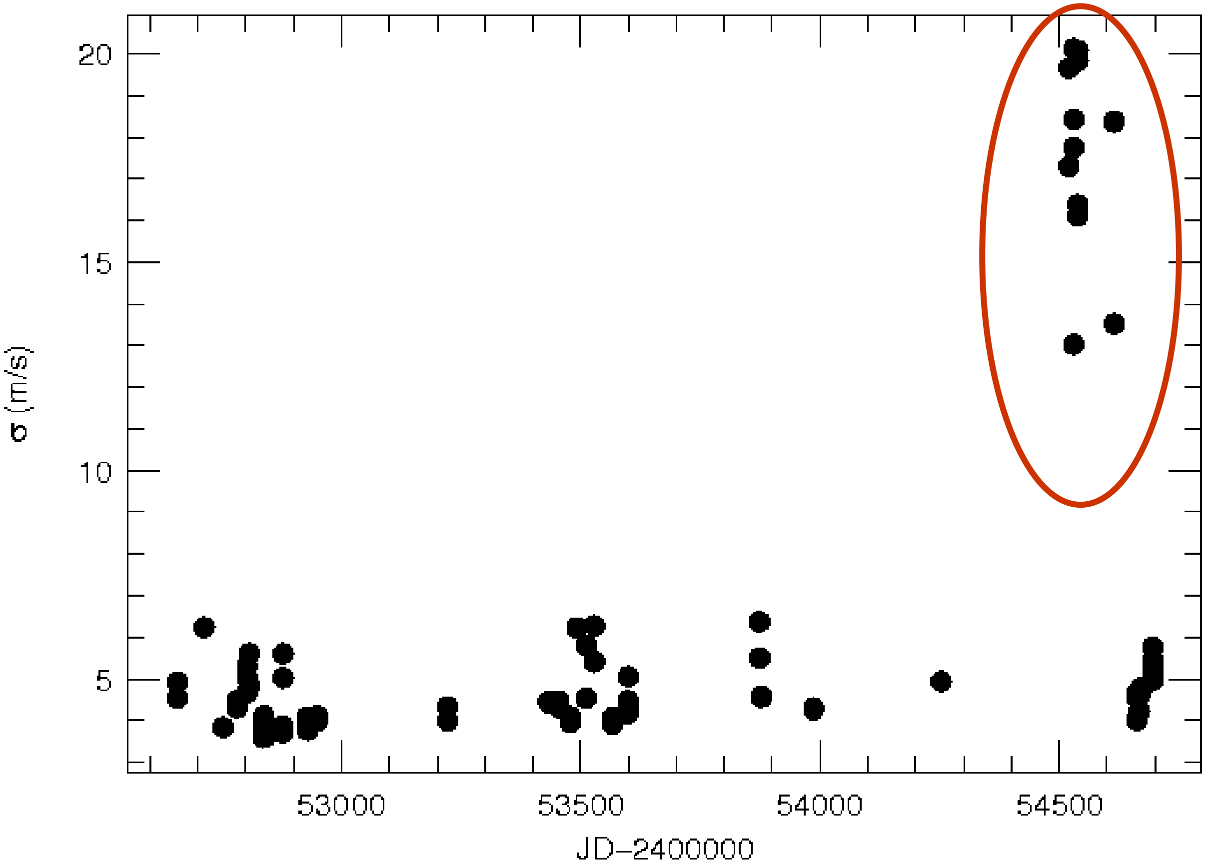




March 1994

Jan 1995

4. Stable Detectors!



5. Intrinsic Stellar Variability (Big Problem!)

Major sources of intrinisic noise in solar-like stars

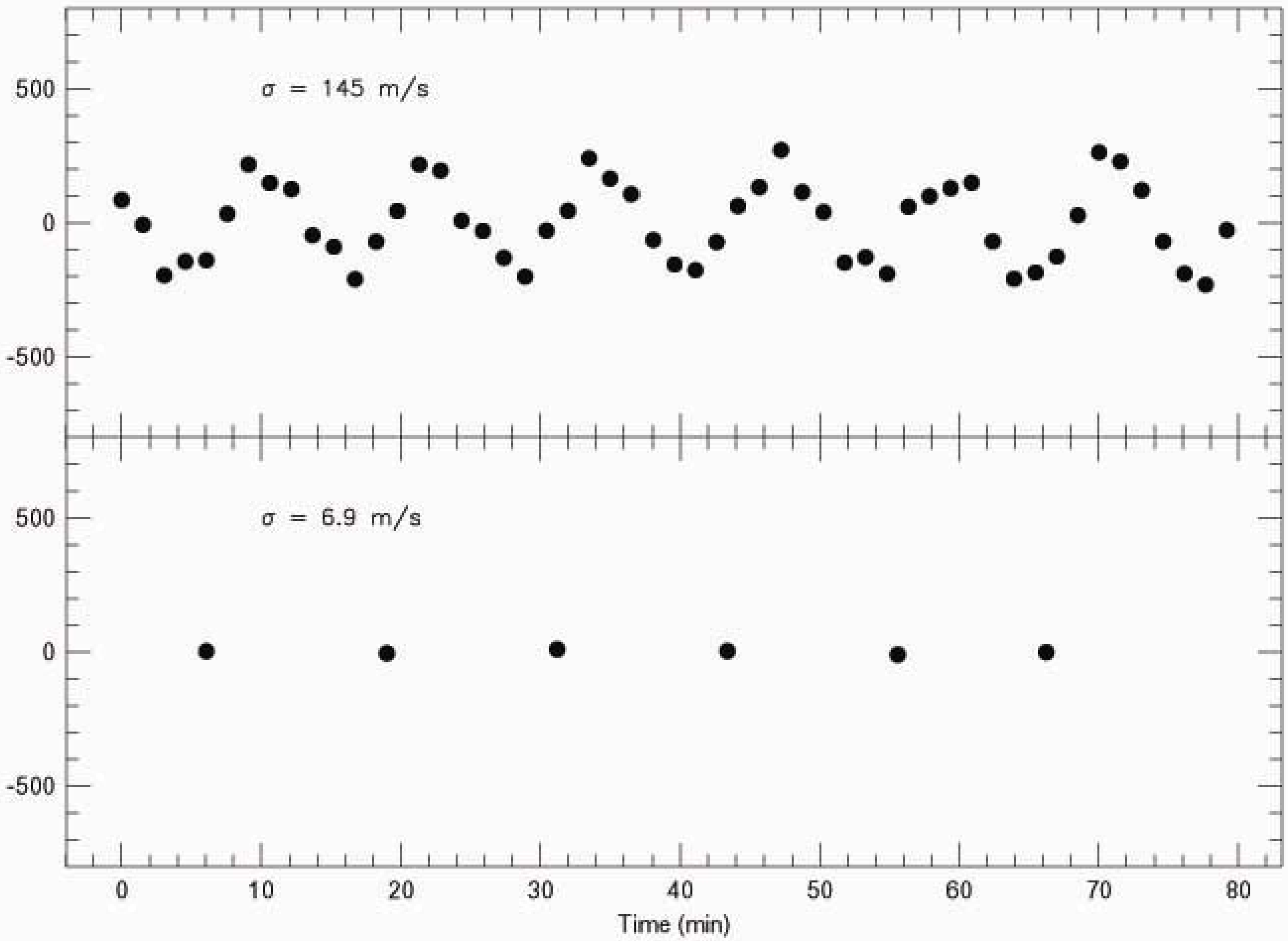
Phenomenon	**Timescales**	**Amp. (m/s)**
Oscillations	5-10 min	0.3-0.5
Spots/Activity	**4-50 days**	**1-100**
Convection	**0.1-20 yrs**	**~10**

No matter how advanced or stable your spectrometer is, the ultimate RV precision will be limited by intrinsic stellar variability.

„Quietest“ stars may be constant to no better than 0.5 – 1 m/s

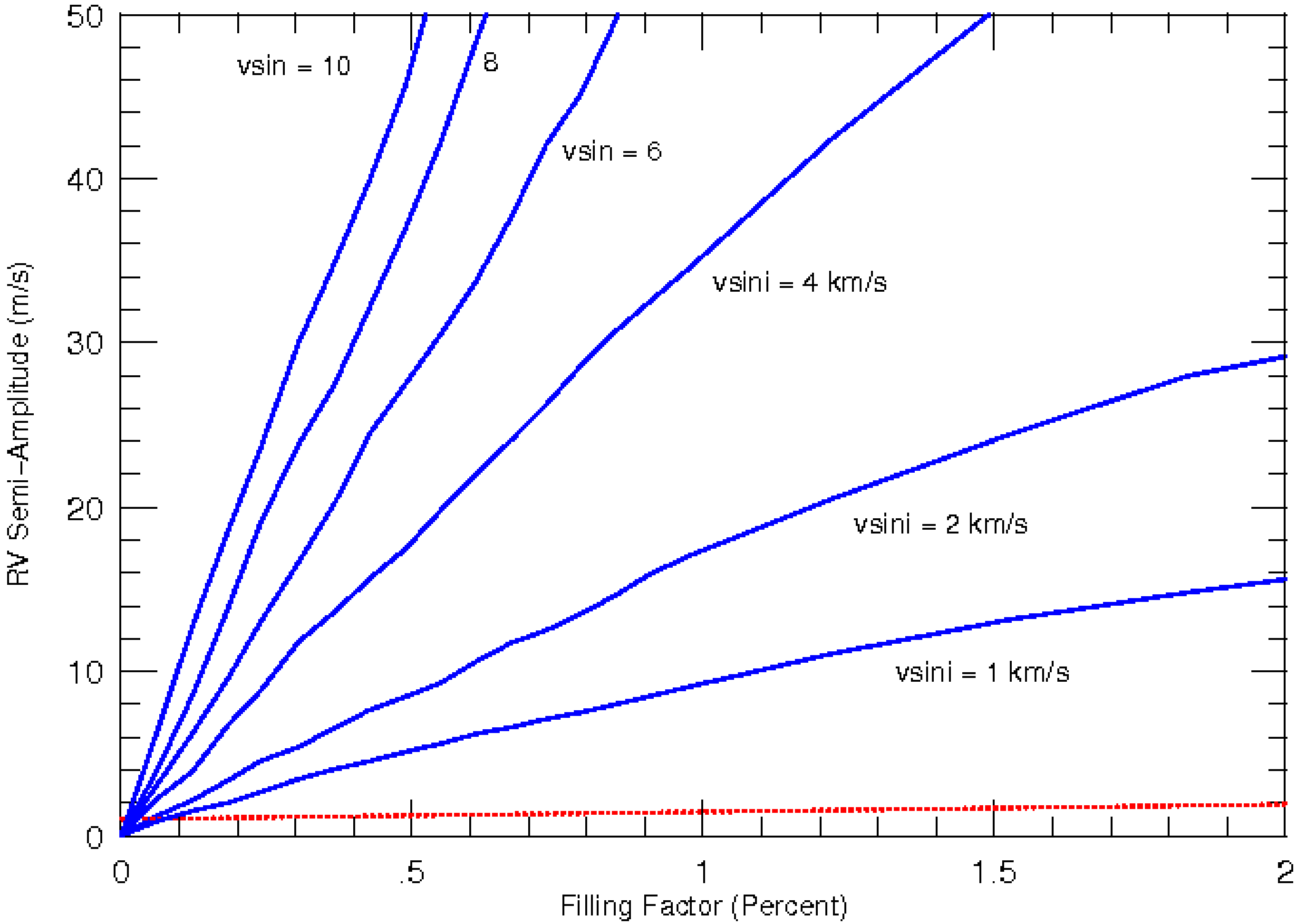
Is this a show stopper!

Stellar Oscillations are not a problem



A rapidly oscillation Ap star with P = 11 min

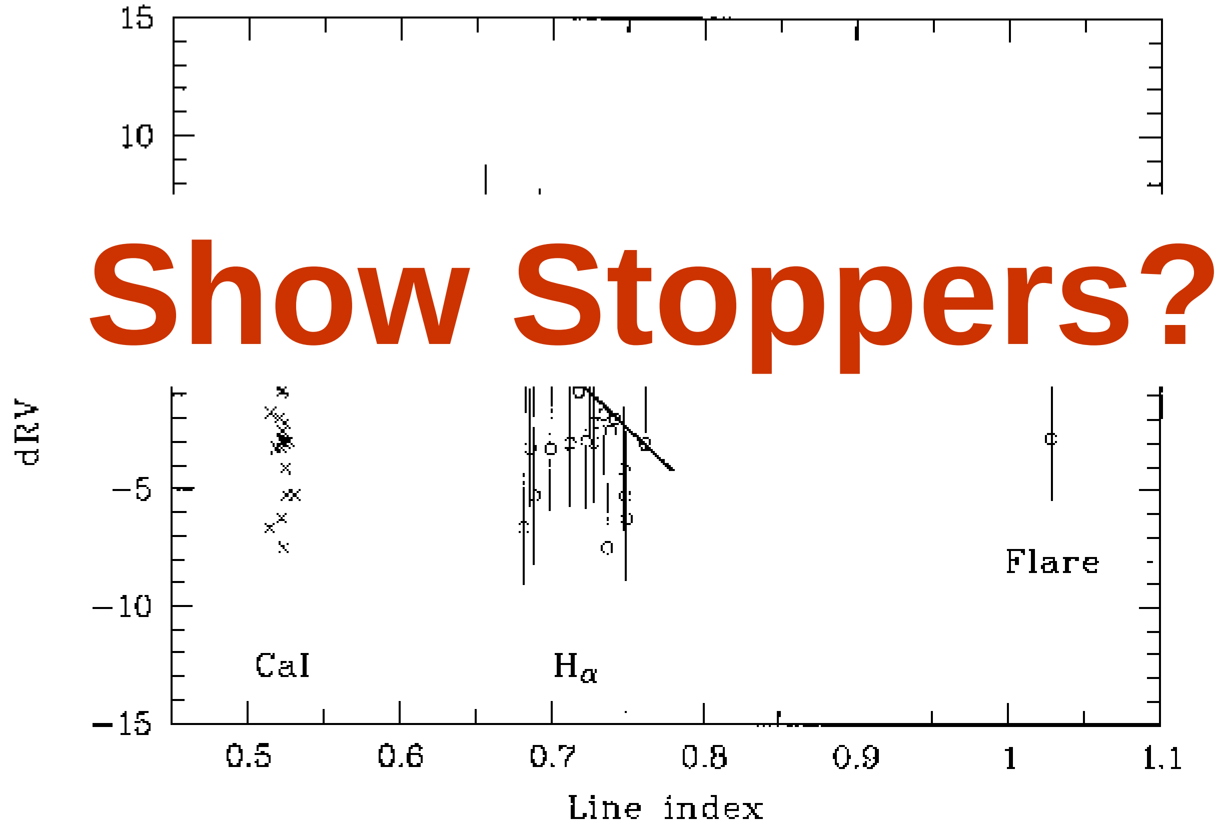
Spots are a problem



Convective Red/Blue Shifts also a Problem

Barnard‘s star (M2)

Kürster et al. 1997



Show Stoppers?

RV variations with amplitude of 5 m/s and time scales ~30-60 days. Not a planet but changes in the convection pattern.

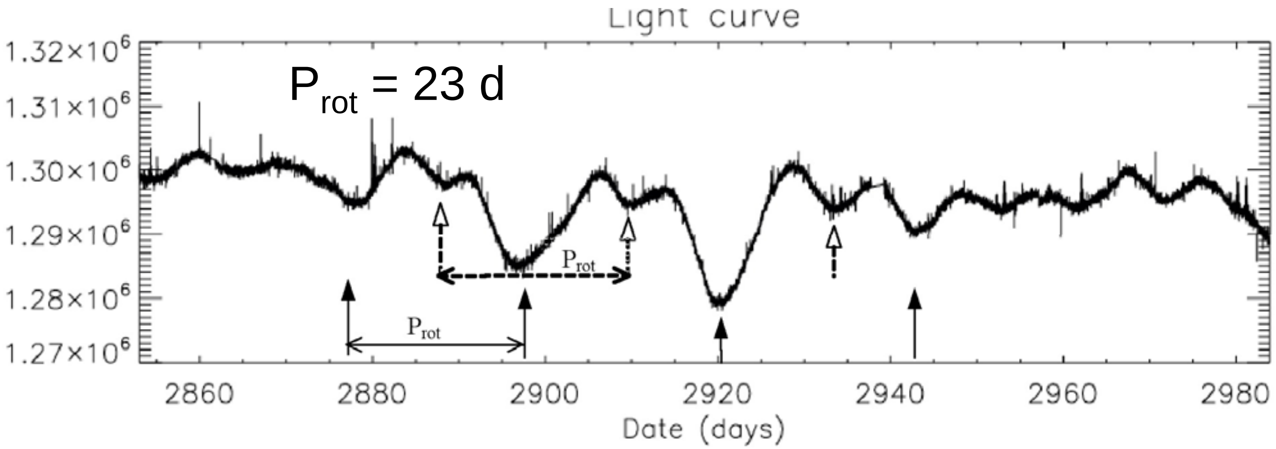
Two cases:

1. Planets with periods less than time scales of activity (few measurements)
2. Planets with periods longer than time scales of activity (lots of measurements)

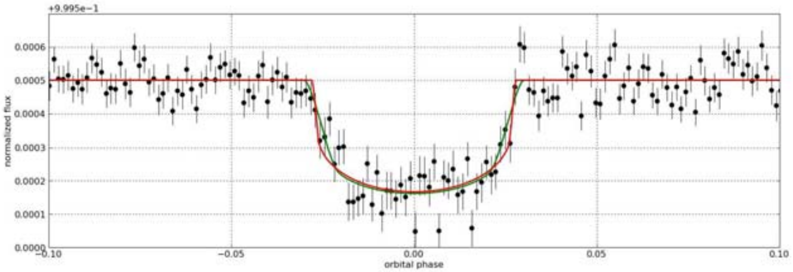
Case 1) : Orbital periods of the exoplanets are much shorter than stellar variations

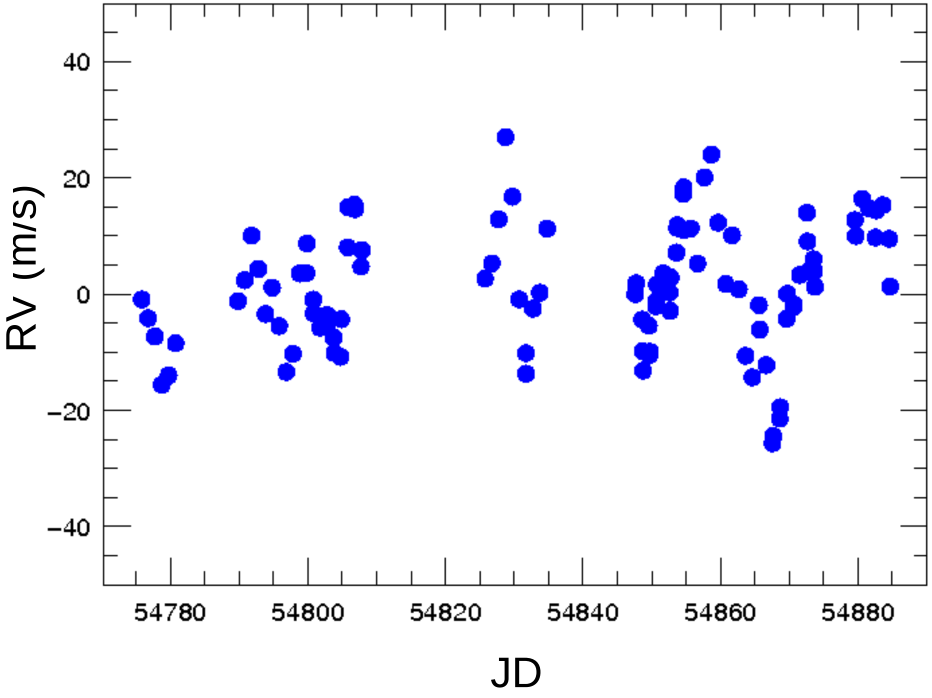
- RV contribution of activity is a constant offset
- Activity variations (excluding flares) are days (spot evolution) to weeks (rotation).
- so long as $P_{orbit} < P_{rot}$

Example: CoRoT-7b



P_{rot} = 23 d

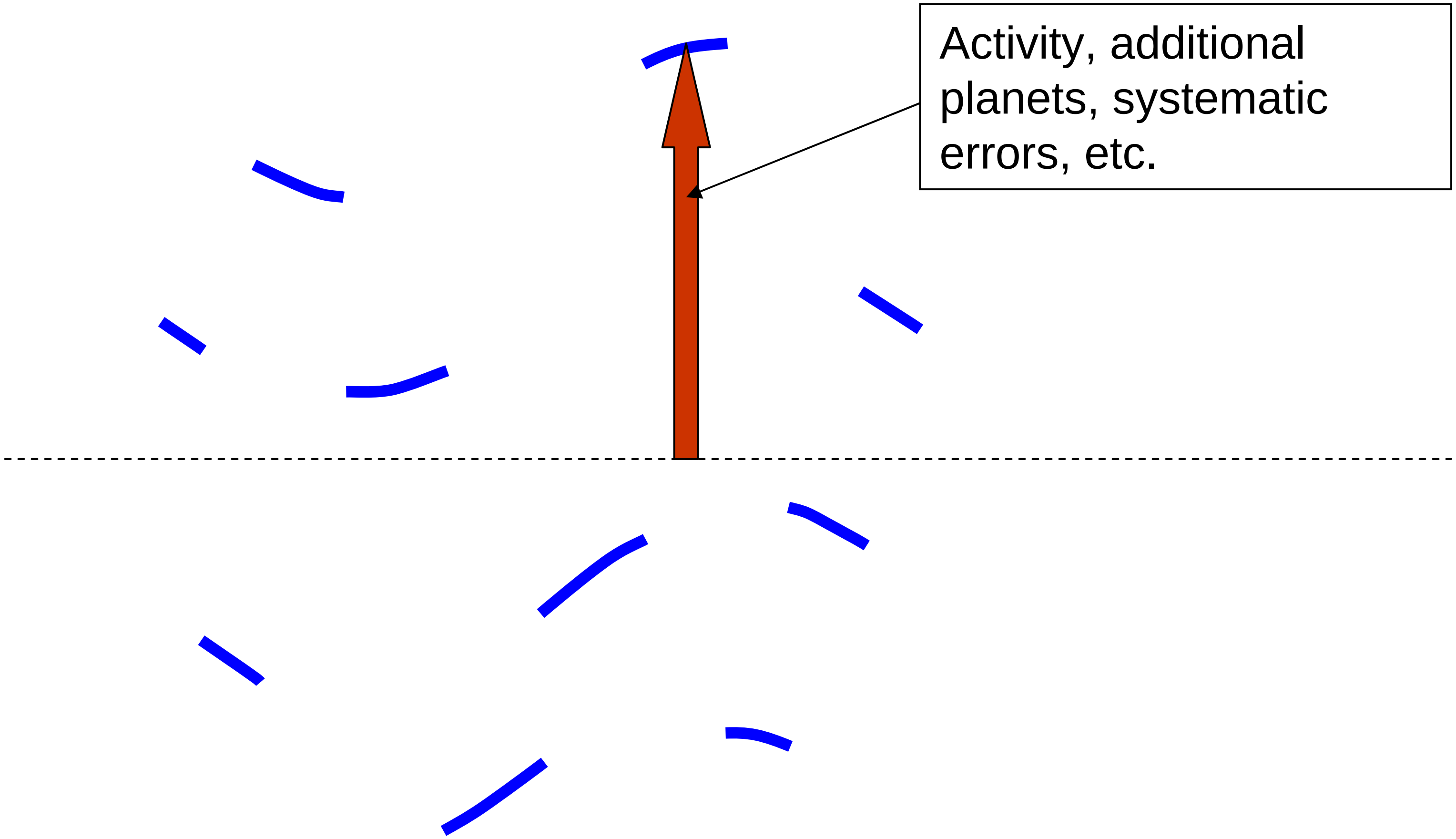




P_{rot} = 23 d

P_{planet} = 0.85 d

A simple way to remove the acvitity signal



Activity, additional planets, systematic errors, etc.

If the RV variations due to activity, additional planets, or systmatic noise are constant on a given night, then these can be simply subtracted and the segments of the CoRoT-7b sine wave „stiched together“

Two simple and reasonable assumptions:

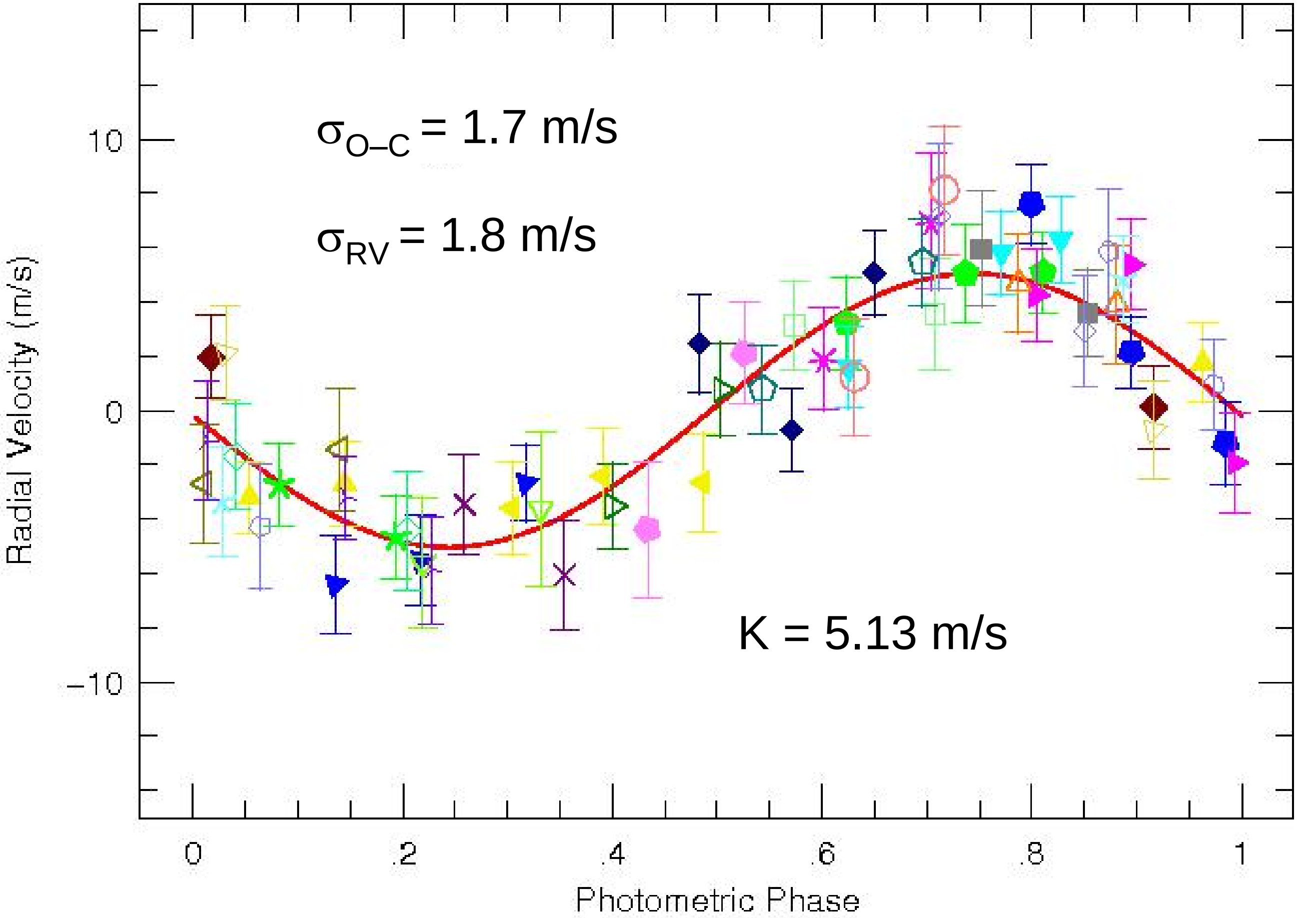
1) A 0.85 d period is present in the RV data

   - Reasonable given Leger, Rouan, Schneider et al. (2009)

2) RV Variations from other phenomena (activity, other planets, systematic errors) over $\Delta T < 4$ hours is small.

   - $\Delta\phi_{rot} = 0.01$, $\Delta RV < 0.5$ m/s
   - $\Delta RV_{planets} = 0 \pm 0.9$ m/s

use 27 nights with 2-3 measurements separated by 2-4 hours



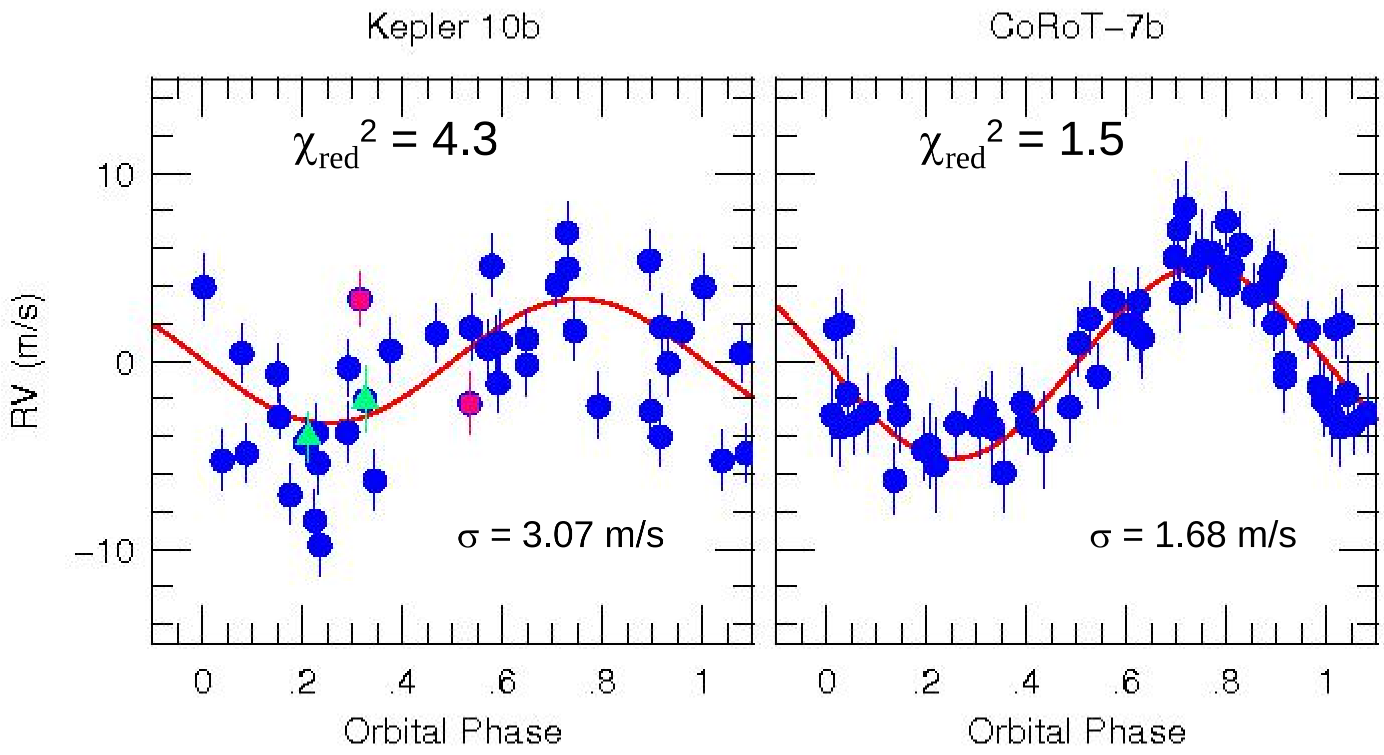
σ_{O-C} = 1.7 m/s

σ_{RV} = 1.8 m/s

K = 5.13 m/s

Zero point offsets and phase are the only free parameters. The RV phase agrees with transit phase to within 0.01 phase

Kepler-10b versus CoRoT-7b: Inactive versus Active



M_{star} = 0.895 ± 0.06 M_{sun}

R_{star} = 1.056 ±0.02 R_{sun}

M_{Pl} = 4.56 ±1.23 M_{Earth}

R_{Pl} = 1.416 ±0.025 R_{Earth}

ρ_{Pl} = 8.8 ±2.5 cgs

M_{star} = 0.91 ±0.03 M_{sun}

R_{star} = 0.82 ±0.04 R_{sun}

M_{Pl} = 7.29 ±1.35 M_{Earth}

R_{Pl} = 1.58 ±0.10 R_{Earth}

ρ_{Pl} = 10.2 ±2.7 cgs

Case 2) : Orbital Periods of the exoplanets are longer or comparable to the stellar variations

- Activity is a source of noise that adds to the measurement error

- Unfortunately, this is not white noise

- RV variations due to activity can be stochastic, periodic, and semi-periodic

- Spot evolution, migration etc. coupled with sampling window may produce fake signals

- The only way to beat down the stellar noise is not with better precision, but with more measurements spanning the timescales of the stellar noise

How many observations are needed?

Suppose you have and RV precision of 1 m/s in order to detect an amplitude of 10 cm/s :

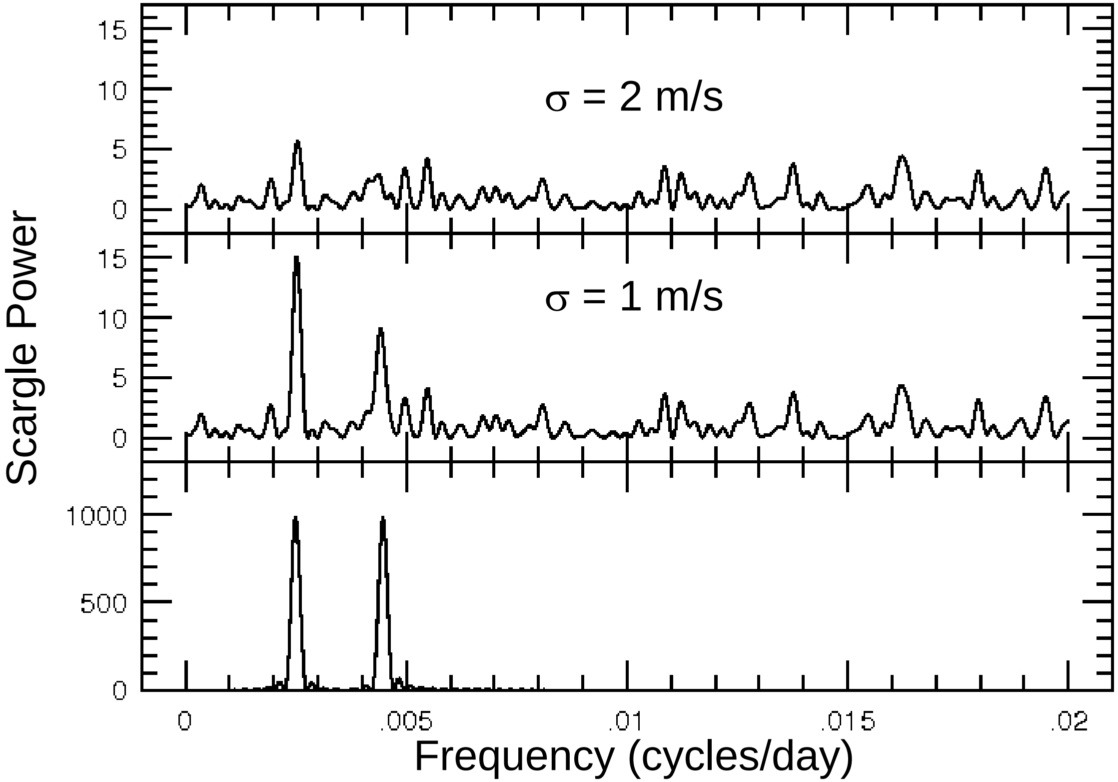
~ 40 measurements to detect an amplitude comparable to your measurement error, well sampled over an orbital period

100 measurements per „phase point“ to get a mean error of 10 cm/s

→ ~4000 measurements

= 4000 x 0.25 x 1.25 = 1250 hours = 140 nights on target for one star.

In principle this should work:

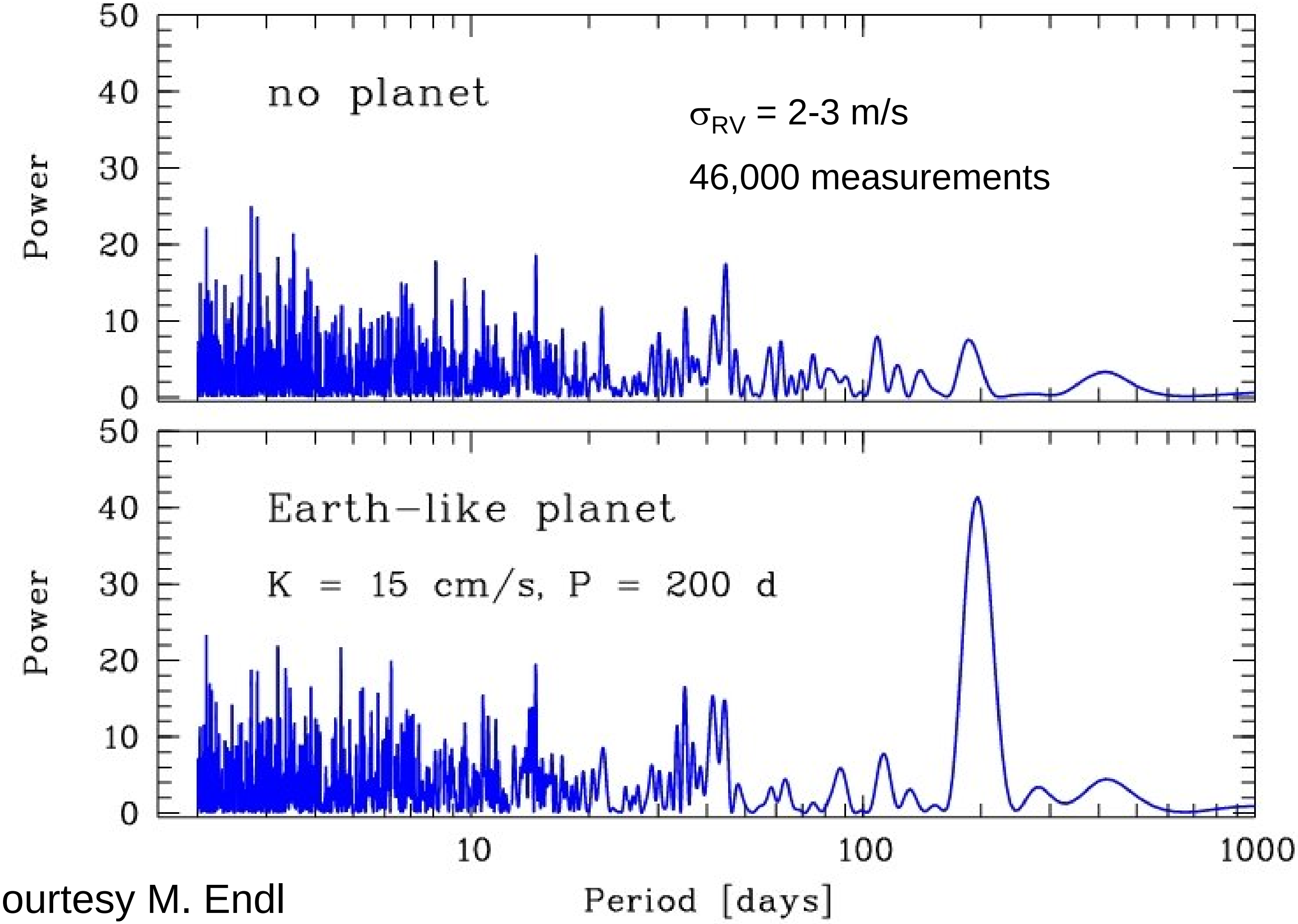


An ideal world: Daily sampling, 4000 measurements, Gaussian noise

P_1 = 400 d, Amp = 10 cm/s (Earth-like)

P_2 = 225 d, Amp = 10 cm/s (Venus-like)

Simulations using real data:

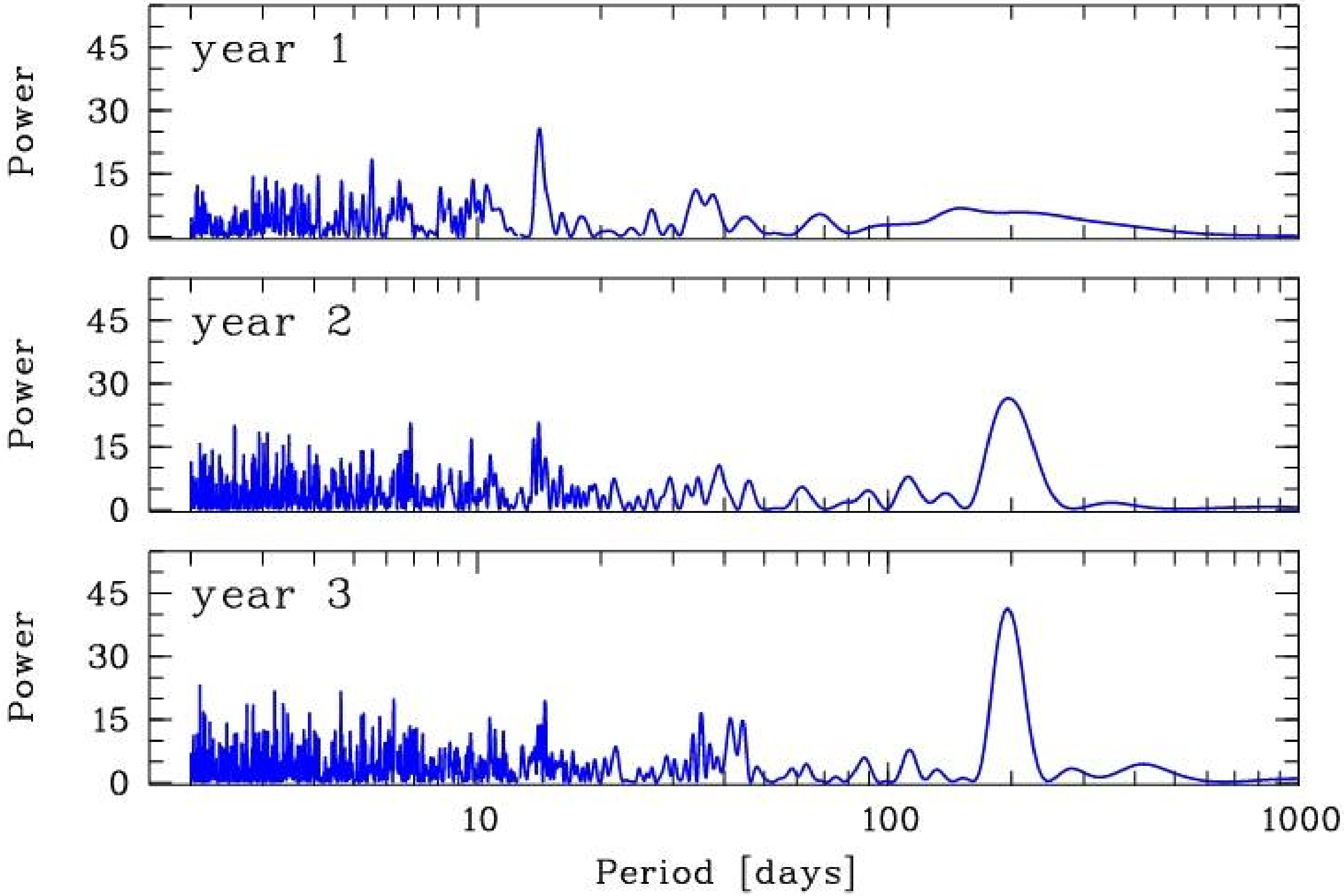


σ_{RV} = 2-3 m/s

46,000 measurements

Courtesy M. Endl

Simulations using real data:



What will limit you in practice:

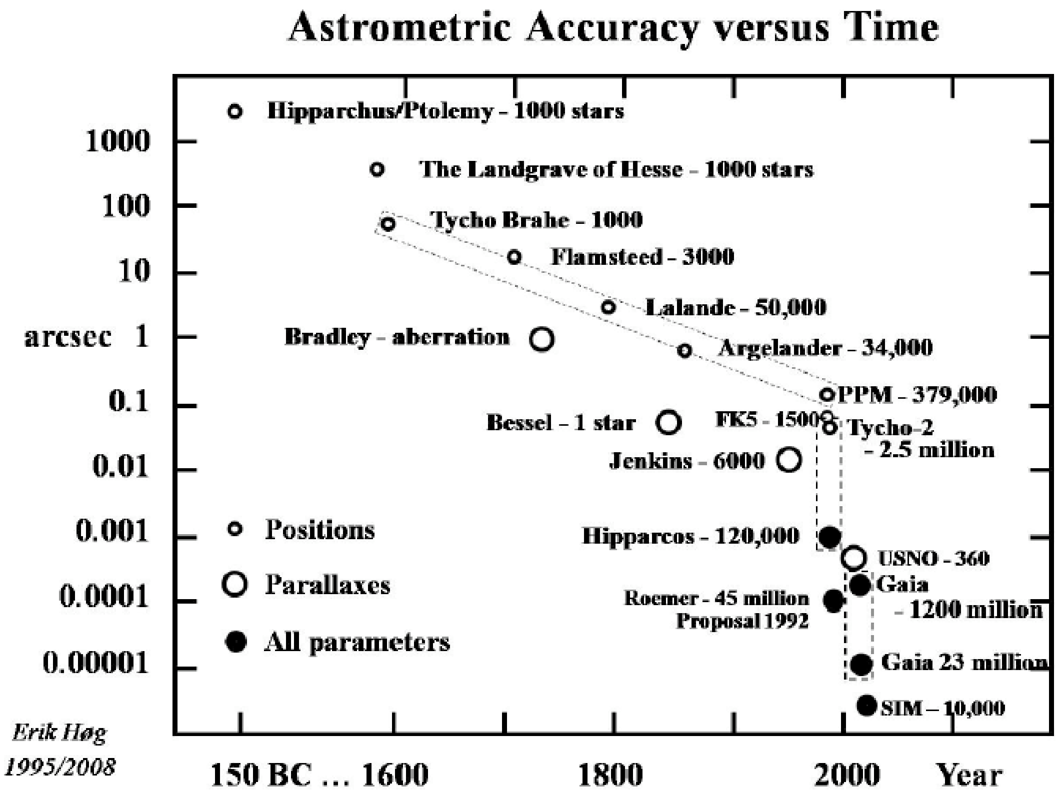
1. Spot evolution, migration coupled with sampling may introduce spurious periods (frequencies) that are not averaged out
2. Insufficient data
3. Unknown sytematic errors: „the things we don‘t know that we don‘t know“ – Donald Rumsfeld

- You can think of everything to minimize your systematic errors, but the show stopper more likely will come from something you did not consider.
- An understanding of the systematic errors can only come through making measurements.

Take home messages:

1. RV Precision has increased by more than a factor of 2000 in last 50 years
2. Improved wavelength calibration and instrument stablity should see a precision of 10 cm/s within the next 5 years
3. The ulitimate measurement „error“ is limited by the intrinsic stellar variability (precision versus accuracy)
4. Current RV precision is sufficient to detect Superearths and possibly Earth-mass planets in the habitable zone of solar like stars…unless systematic errors stop us (venturing into new terrain).
5. Telescope resources that are required are enormous one telescope + 10 stars → 1400 nights. Multiple programs are required to get a sufficient sample size

II. And a few words on Astrometry…

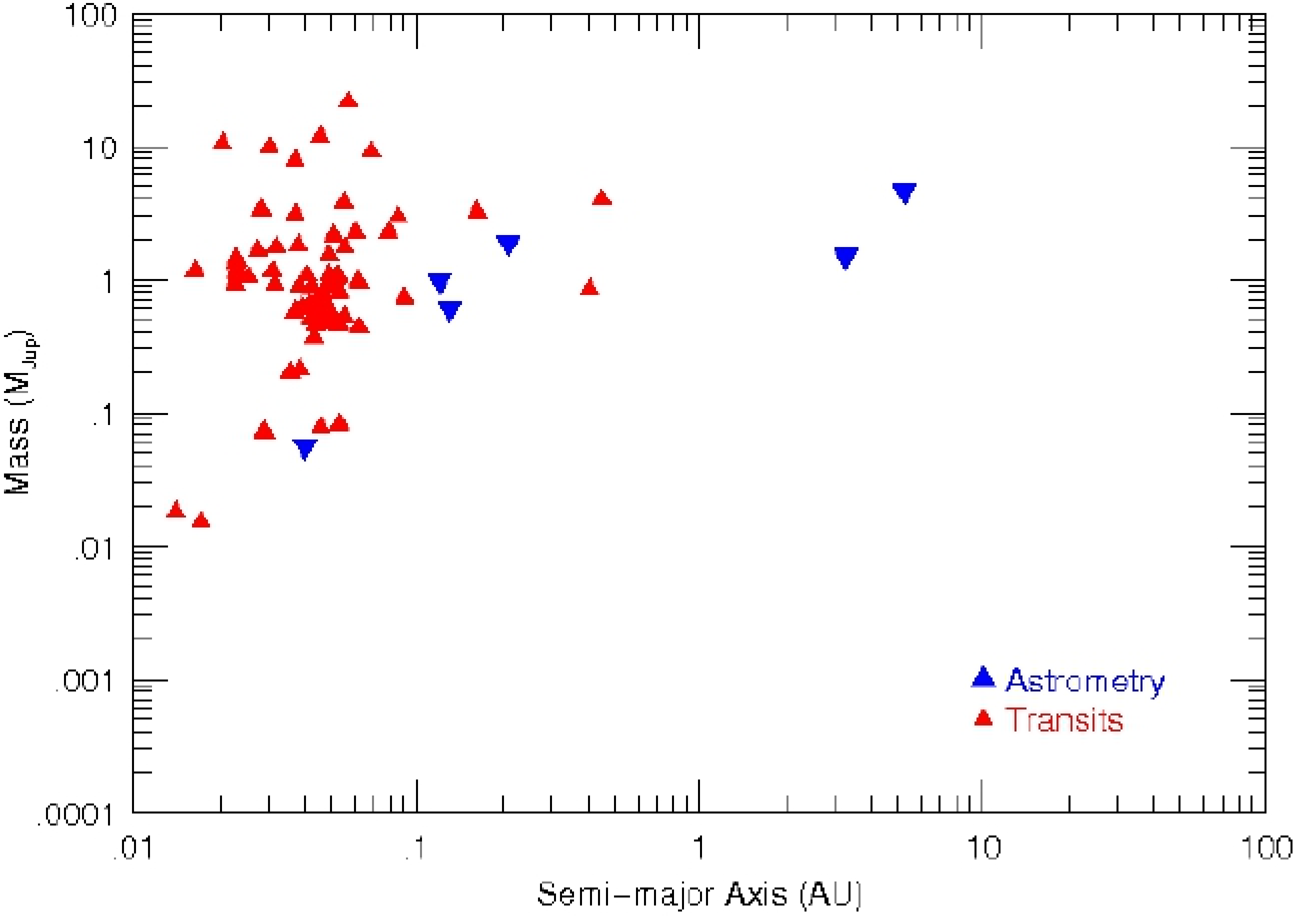


Ground-based astrometric measurements have only increased by a factor of ~10 in the past 50 years.

Comparison between Radial Velocity Measurements and Astrometry.

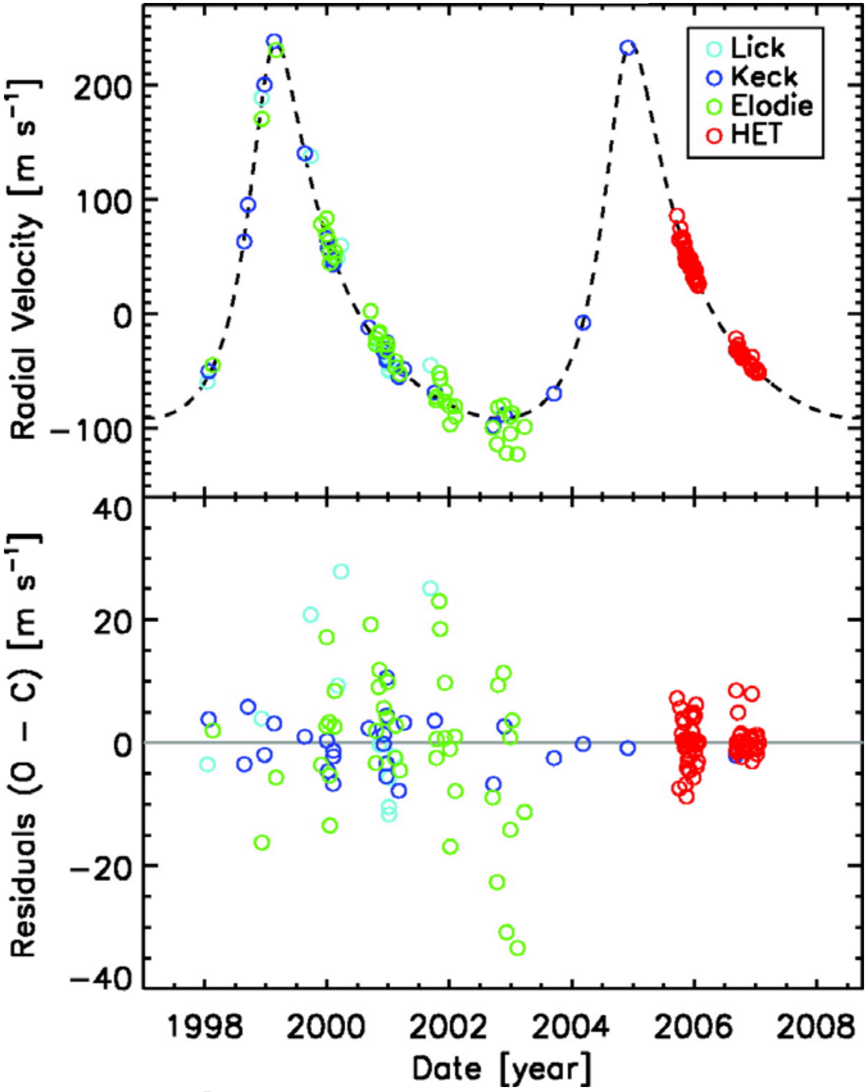
Astrometry and radial velocity measurements are fundamentally the same: you are trying to measure a displacement on a detector

Radial Velocity	**Astrometry**
1. Measure a displacement of a spectral line on a detector	1. Measure a displacement of a stellar image on a detector
2. Thousands of spectral lines (decrease error by $\sqrt{N_{\text{lines}}}$)	2. One stellar image
3. Hundreds of reference lines (Th-Ar or Iodine) to define „plate solution“ (wavelength solution)	3. 1-10 reference stars to define plate solution
4. Reference lines are stable	4. Reference stars move!
Precision increase in 50 years: factor of 1000-2000	Precision increase in 50 years: factor of 10-100

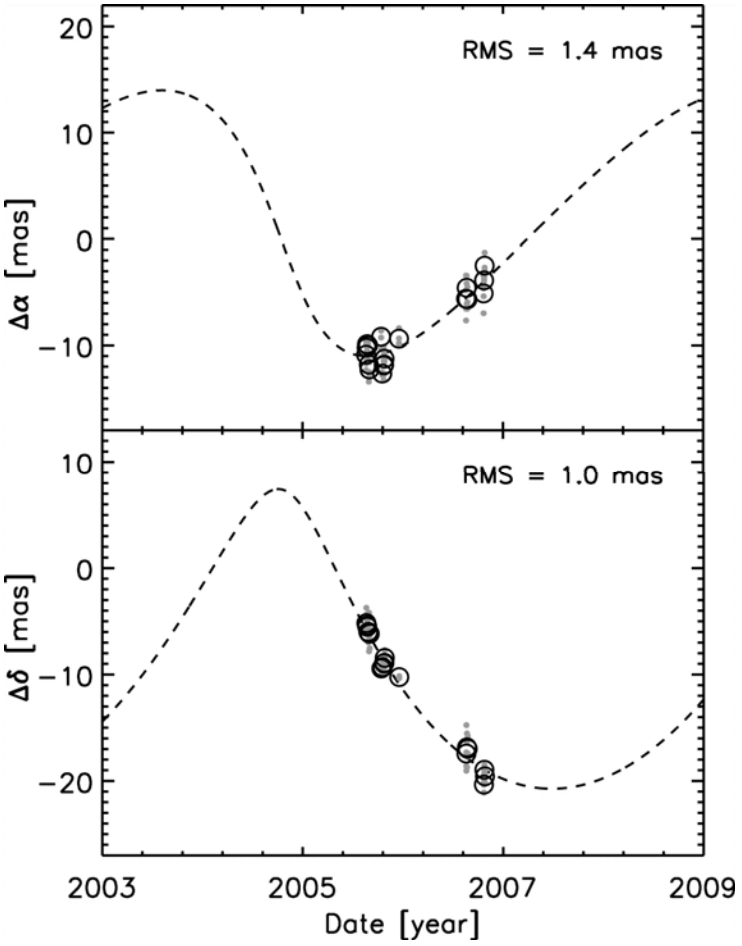

100
10
1
.1
.01
.001
.0001
Mass (M_{Jup})
.01
.1
1
10
100
Semi-major Axis (AU)
▲ Astrometry
▲ Transits

Why you need the true mass!

HD 33636 B



Bean et al. 2007AJ....134..749B



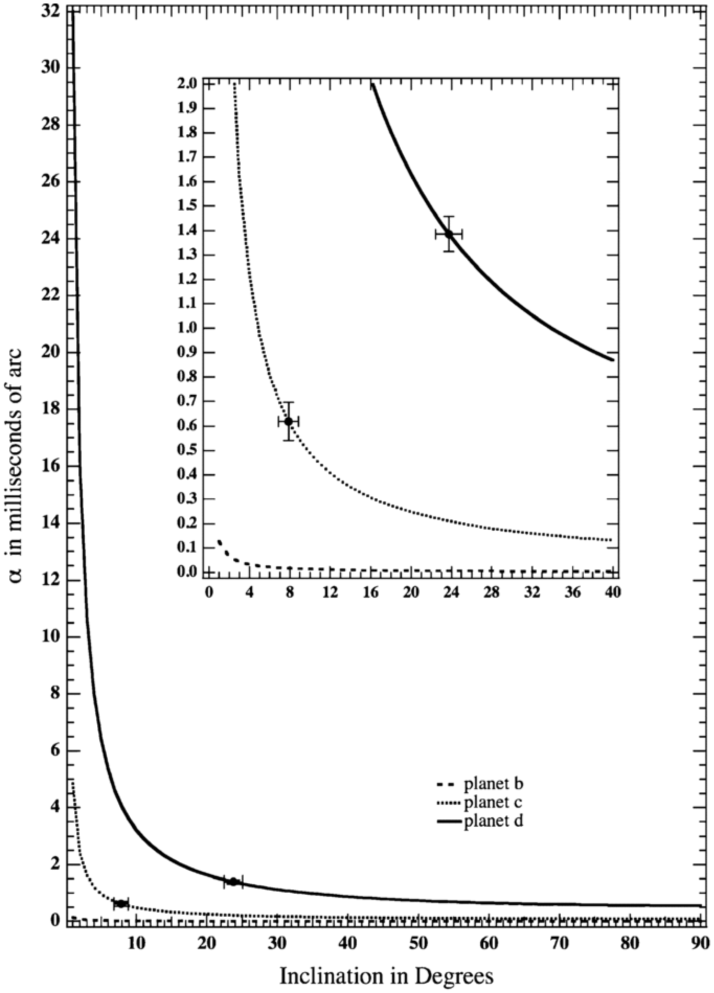
P = 2173 d

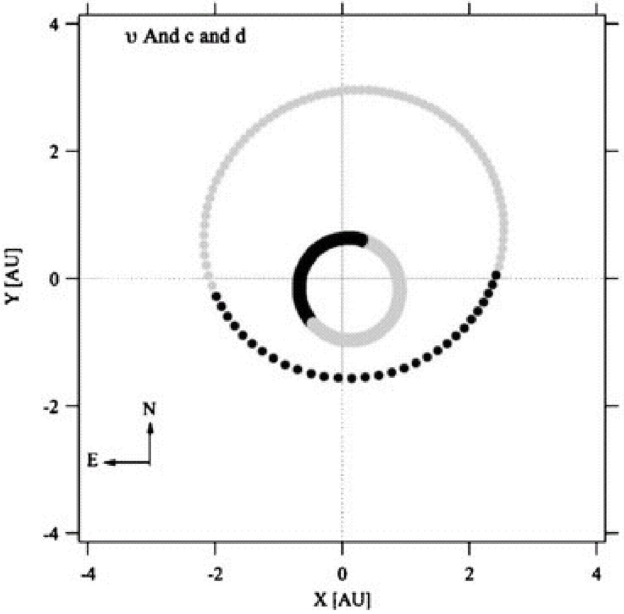
Msini = 10.2 M_{Jup}

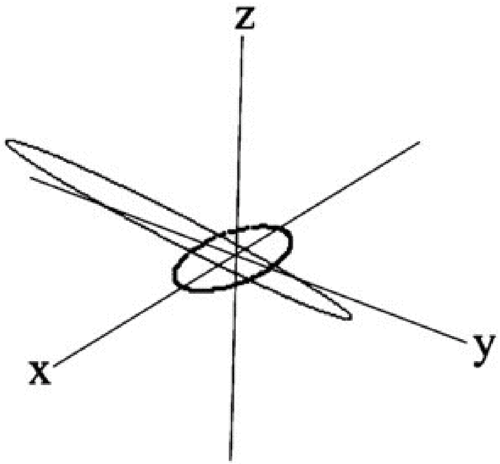
i = 4 deg → m = 142 M_{Jup}

= 0.142 M_{sun}

The misaligned System of υ And







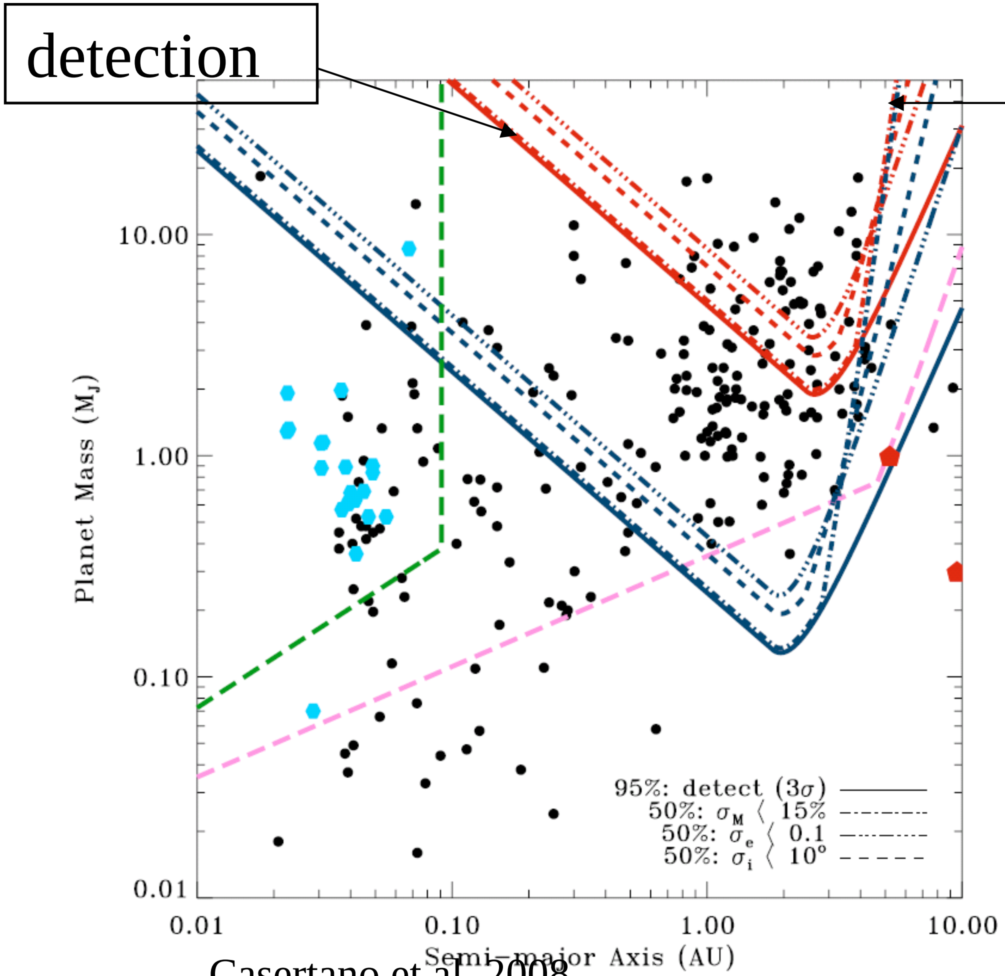
McArthur et al. 2010

Misaligned systems for non-transiting planets can only come from astrometry

GAIA: The start of the Golden Era of Astrometric Detections

detection

Parameters determined



Casertano et al. 2008

Fig. 22. Gaia discovery space for planets of given mass and orbital radius compared to the present-day sensitivity of other indirect detection methods, namely Doppler spectroscopy and transit photometry. Red curves of different styles have the same meaning as in Fig. 21 assuming a 1-$M_\odot$ G dwarf primary at 200 pc, while the blue curves are for a 0.5-$M_\odot$ M dwarf at 25 pc. The radial velocity curve (pink line) is for detection at the $3\sigma_{RV}$ level, assuming σ_{RV} = 3 m s^{-1}, $M_\star = 1\ M_\odot$, and 10-yr survey duration. For transit photometry (green curve), the assumptions of Gaudi et al. (2005) are used, i.e. σ_V = 5 milli-mag, $S/N = 9$, $M_\star = 1\ M_\odot$, $R_\star = 1\ R_\odot$, uniform and dense (>1000 datapoints) sampling. Black dots indicate the inventory of exoplanets as of September 2007. Transiting systems are shown as light-blue filled pentagons. Jupiter and Saturn are also shown as red pentagons.

Red: G-stars Blue: M Dwarfs

Number of Expected Planets from GAIA

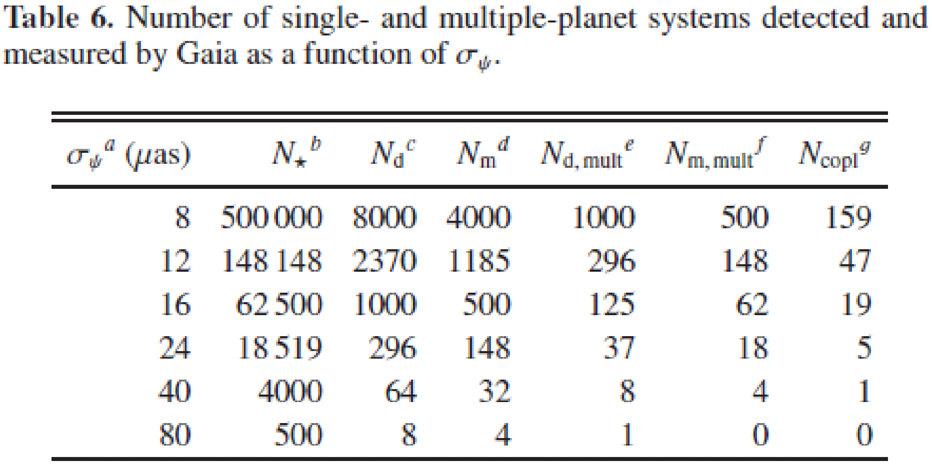


Table 6. Number of single- and multiple-planet systems detected and measured by Gaia as a function of σ_ψ.

$\sigma_\psi{}^a$ (μas)	$N_\star{}^b$	$N_\mathrm{d}{}^c$	$N_\mathrm{m}{}^d$	$N_\mathrm{d,\,mult}{}^e$	$N_\mathrm{m,\,mult}{}^f$	$N_\mathrm{copl}{}^g$
8	500 000	8000	4000	1000	500	159
12	148 148	2370	1185	296	148	47
16	62 500	1000	500	125	62	19
24	18 519	296	148	37	18	5
40	4000	64	32	8	4	1
80	500	8	4	1	0	0

8000 Giant planet detections
4000 Giant planets with orbital parameters determined
1000 Multiple planet detections
500 Multiple planets with orbital parameters determined

The detections will require ground-based RV measurements to derive the orbit. This will further tax telescope resourses

What SIM-Lite could have done

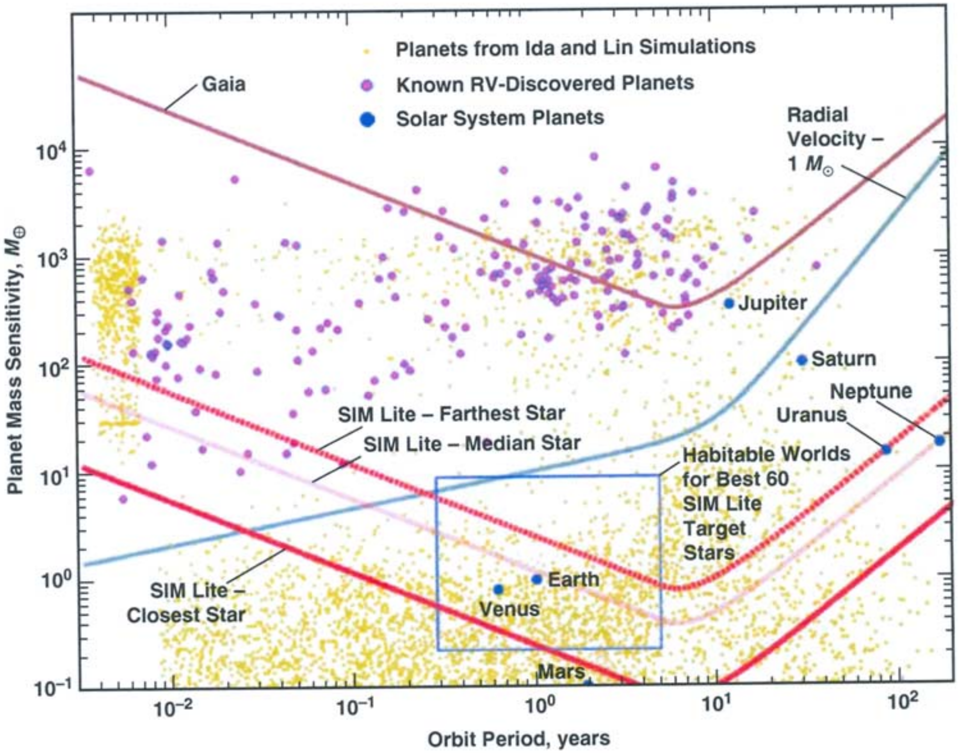


Figure 1-3. Detectability of planets by SIM Lite, Gaia, and radial velocity (RV). The regions above each curve are accessible to the respective mission/technique. The two red curves show the detection thresholds for the closest and farthest among the 60 FGK stars to be probed by SIM Lite. Small rocky worlds circling in the habitable zones of these stars will fall within the box near the bottom of the figure. SIM Lite offers excellent detectability of these planets. In contrast, RV (accuracy ≈ 1 m/s) and Gaia lack the sensitivity to probe this region. The pale green dots show predicted planets from planet formation theory (Ida and Lin 2004), the purple dots show known planets, mostly from RV work, and the blue dots show the planets of our Solar System.

The Evolution of Space Interferometry Mission (SIM)

Take home messages:

1. Current astrometric precision is currently too poor to have an impact
2. In spite of being the oldest search method it is the only one to have not discovered an exoplanet (precision + sensitive to long periods)
3. GAIA should usher in a „Golden Age“ of astrometric detections of giant planets.
4. With the loss of SIM-Lite the burden falls on the RV community to find habitable terrestrial planets for future characterization